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Payload and survivability tradeoffs in the presence of risk

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THESIS

PAYLOAD AND SURVIVABILITY TRADEOFFS IN THE PRESENCE OF RISK

by

Mary-Elyse Janowski

June 2013

Thesis Co-Advisors: Fotis Papoulias
Oleg Yakimenko

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The objective of this thesis research is to find an optimized throughput plan for ship sustainment operations that will assist in minimizing the overall risk of transportation of supplies. Our main goal is to maximize throughput when considering cargo ship size, quantity, speed, range, and risk when traversing through a designated travel area. Data collected from previous theses, analytical equations, and computer modeling programs assist in computing this maximum throughput load. The results of this thesis demonstrate that a thorough awareness and consideration of the survivability of supply vehicles must be analyzed to mitigate increased risk.

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PAYLOAD AND SURVIVABILITY TRADEOFFS IN THE PRESENCE OF RISK

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Submitted in partial fulfillment of the
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ABSTRACT

The objective of this thesis research is to find an optimized throughput plan for ship sustainment operations that will assist in minimizing the overall risk of transportation of supplies. Our main goal is to maximize throughput when considering cargo ship size, quantity, speed, range, and risk when traversing through a designated travel area. Data collected from previous theses, analytical equations, and computer modeling programs assist in computing this maximum throughput load. The results of this thesis demonstrate that a thorough awareness and consideration of the survivability of supply vehicles must be analyzed to mitigate increased risk.

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LIST OF ACRONYMS AND ABBREVIATIONS

B	Length of Ship's Beam
b	Normalized Beam, Beam length over lethal area length, B/D
CCL	Cargo Carriage Load [LT]
D	Width of Lethal Area
EHP	Effective Horsepower [hp]
$\mathrm{F}n_{\mathrm{vol}}$	Volumetric Froude Number
GPS	Global Positioning System
ISO	International Standard Organization
l	Length Factor
L_A	Actual length
L/D	Lift to Drag Ratio
LF	Loading factor
L_V	Volumetric length
MCR	Maximum Continuous Range
MSC	Military Sealift Command
OPC	Overall Propulsion Efficiency
P_{H}	Probability of Hit
$\mathrm{P}_{\#\mathrm{H}}$	Probability of #Ships being Hit
$\mathrm{P}_{\mathrm{H\#/S\#}}$	Probability of H# Getting Hit and S# Surviving (kill tree)
P_{S}	Probability of Survival
$\mathrm{P}_{\#\mathrm{S}}$	Probability of #Ships Surviving
R	Risk radius
r	Normalized Risk, Risk radius over lethal area length, R/D
R_{NM}	Range [NM]
SES	Surface Effect Ships
SFC	Standard Fuel Consumption [lbs/hp/hr]
SHP	Shaft Horsepower [hp]
V_k	Velocity [NM/hr]
VSM	Very Simple Model
W_{cc}	Weight of Cargo Carriage [LT]
W_f	Weight of Ship Fuel [LT]
W_m	Weight of Ship Machinery [LT]

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Sincere thanks to my thesis advisor, Professor Fotis Papoulias, for his continued direction and guidance through this difficult task. His expertise and skill provided me with a clear understanding of this research. His assistance allowed me to excel in successfully discovering more ways to allow the U.S. Navy to function more efficiently.

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I. INTRODUCTION AND BACKROUND STUDIES

A. INTRODUCTION

Many new concepts of autonomous systems have been revolutionizing our military's operations and reducing our manpower of military forces. These new concepts are becoming more and more advanced throughout the years. In our near future, autonomous vehicles will be playing essential roles in the ability of our Navy to deliver logistical supplies to littoral ship vessels. These autonomous systems will make it easier for these ships to complete their military operations and reduce the threat to personnel. Two background studies (Sumsion 2008) and (Yeh 2007) provided the basis for this current work. First, we will review the background studies and then provide the justification and the scope of the current study.

B. THROUGHPUT EVALUATION IN THE ABSENCE OF RISK

The research of Yeh, which I will be considering and reviewing in this document, is based on a simple shape of a rectangular hull form. This allowed him to produce some fundamental conclusions with regards to speed, payload, and range trade off studies. Yeh's research focused on an in-depth analysis on the hull characteristics of the container and whether subtle alterations to the bow and stern affected resistance or increased the efficiency of the deliverability rates. In my thesis, we will be utilizing Yeh's research of the effects of speed and range on the throughput delivery of these autonomous containers.

Yeh conducted a variety of parametrical studies, graphing the effects of changing loading factor, specific fuel consumption, and range. Yeh noticed that if either the SFC or range increased, the payload would no longer be a linear function of speed. This linear function is portrayed in Figure 1.Yeh discovered that the maximum payload transferred is most efficient at lower speeds, for these conditions. This is particularly true when holding the loading condition low (Yeh 2007).

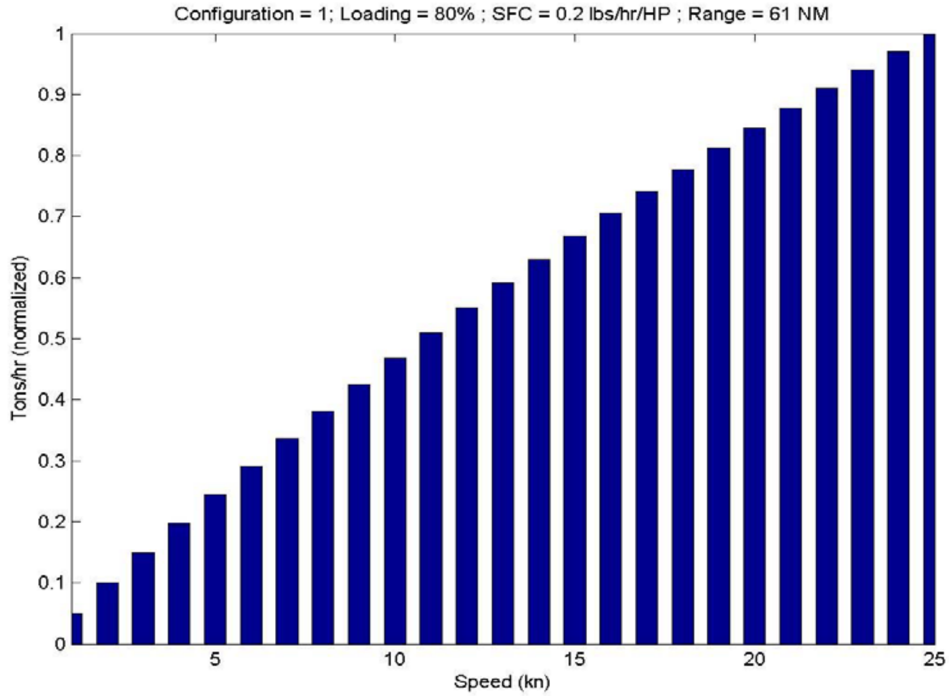

Figure 1. Tons/Hr vs. Speed (From Yeh 2007)

Yeh observed that as SFC and range increased even further, or the loading fraction decreased, that there was a speed beyond which fuel consumption exceeded delivered payload. This point at which SFC exceeds delivered payload is referred to as the critical speed for payload delivery. Payload delivery is only efficient for speeds less than the critical speed. Yeh determined that when SFC and range were increased, there would become a parabolic shape in the representation of throughput vs. speed, inferring that there is an optimum speed that will optimize the amount of throughput delivered. Anything above or below this speed would cause a degradation of the amount of throughput delivered to a specified area. This characteristic is portrayed in Figure 2 (Yeh 2007).

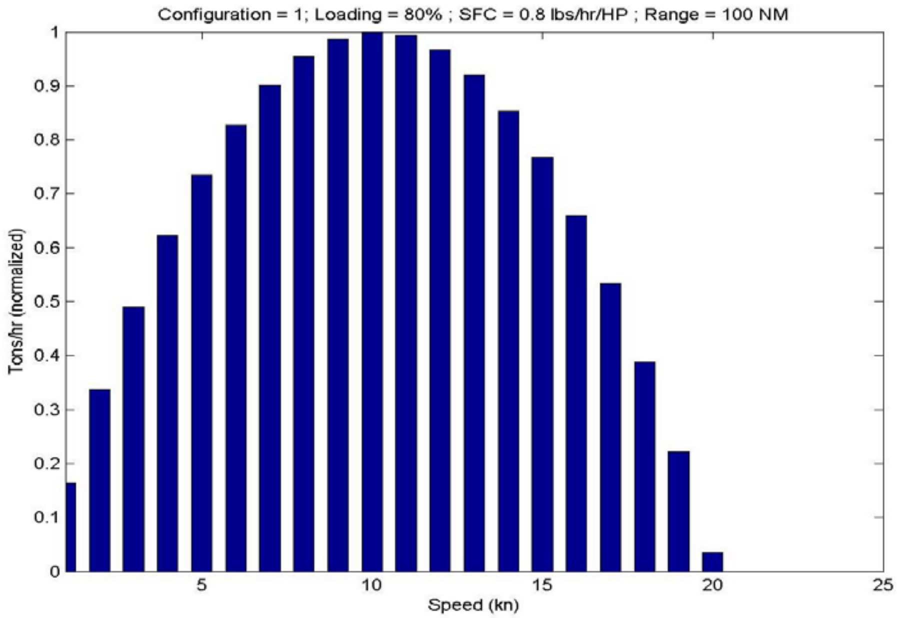

Figure 2. Tons/hr vs. Speed (From Yeh 2007)

One important missing factor and recommendation of Yeh's work was that risk was not taken into consideration in his throughput calculations. This recommendation for future work was completed by William Sumsion in June of 2008. Sumson's contributions that will later be implemented into this paper are explained in the next section (Yeh 2007).

C. TRADEOFFS IN FORRCE SUSTAINMENT OPERATIONS

1. CARGO THROUGHPUT EVALUATION WITH SURVIVABILITY CONSIDERATIONS

a. Introduction to a Throughput Analysis

In Sumsion's thesis he describes throughput as the amount of cargo that a system moves per unit of time. However, it must be noted that there may be several different factors affecting throughput of a water craft, other than just craft size. The primary methods of maximizing cargo throughput are by optimizing ship speed, cargo, sizing, and fuel consumption. However, there is a downside to this optimization. Sumsion makes an example with ship speed. He explains that there are tradeoffs when a mission calls for a rapid cargo delivery of a ship. On one hand the increased speed of the ship will take less time per each transit to deliver cargo. This increases the amount of cargo that potentially can be taken in a given time period. On the other hand, increasing speed will result in higher fuel demands. Therefore, there will be less tonnage available for cargo. The tonnage available for cargo space is equal to, as described in Sumsion's paper, full load displacement minus fuel weight. Later in this paper, we will determine a more specific definition for this cargo load.

(1) Methodology in the Throughput Analysis. In order to compare vessels of various shapes and sizes, a throughput analysis was done starting with an International Standard Organization (ISO) container size. This was used to allow a single dimension to define all three sides of a cuboid. This specific size was used due to the resistance research and other analysis already performed on this size of container. Additionally, this ISO container is largely available throughout the world. The sizing of an ISO container was defined for the analysis as:

Width = w = 8 feet

Length = L = 20 feet

Draft = t = Δ / w*L * (35 / 2240)

Δ= displacement in tons, 35=cubic feet/ton, 2240= pounds/ton

The dimensions of the ISO container will be used as the basic size of the comparing unit called length factor (*l*). This length factor will be used in comparing ships of various sizes that are locked into the ISOS's geometric shape. A ship with a length factor of one will be the size of an ISO container. A ship with a length factor of two will be twice the width, length and draft of a standard ISO container and so on (Sumsion 2008).

Now one must find a method of comparing various sizes and numbers of vessels in throughput. To achieve this, Sumsion explains that the total displacement of all vessels in each system needs to be compatible. If a ship is four times the displacement of a smaller craft, then the comparison between the two will be four small craft and one large craft. However, these two different craft will have different efficiencies in moving through the water since larger craft are more efficient. Sumsion explains that smaller craft are less desirable since they will need more fuel per ton of cargo carried due to smaller sized ships being less fuel inefficient. Hence, displacement can be constant for the comparison, but the cargo will not (Sumsion 2008).

2. Ship Sizing and Length Factor Considerations

Figure 3 portrays a graph that compares how the number of ships varies with length factor and displacement per ship. As displayed below, the larger the length factor, the larger the displacement per ship. Figure 3 also portrays how when length factor increases, the number of ships produced goes down. The ships are scaled by the length factor *(l)*.

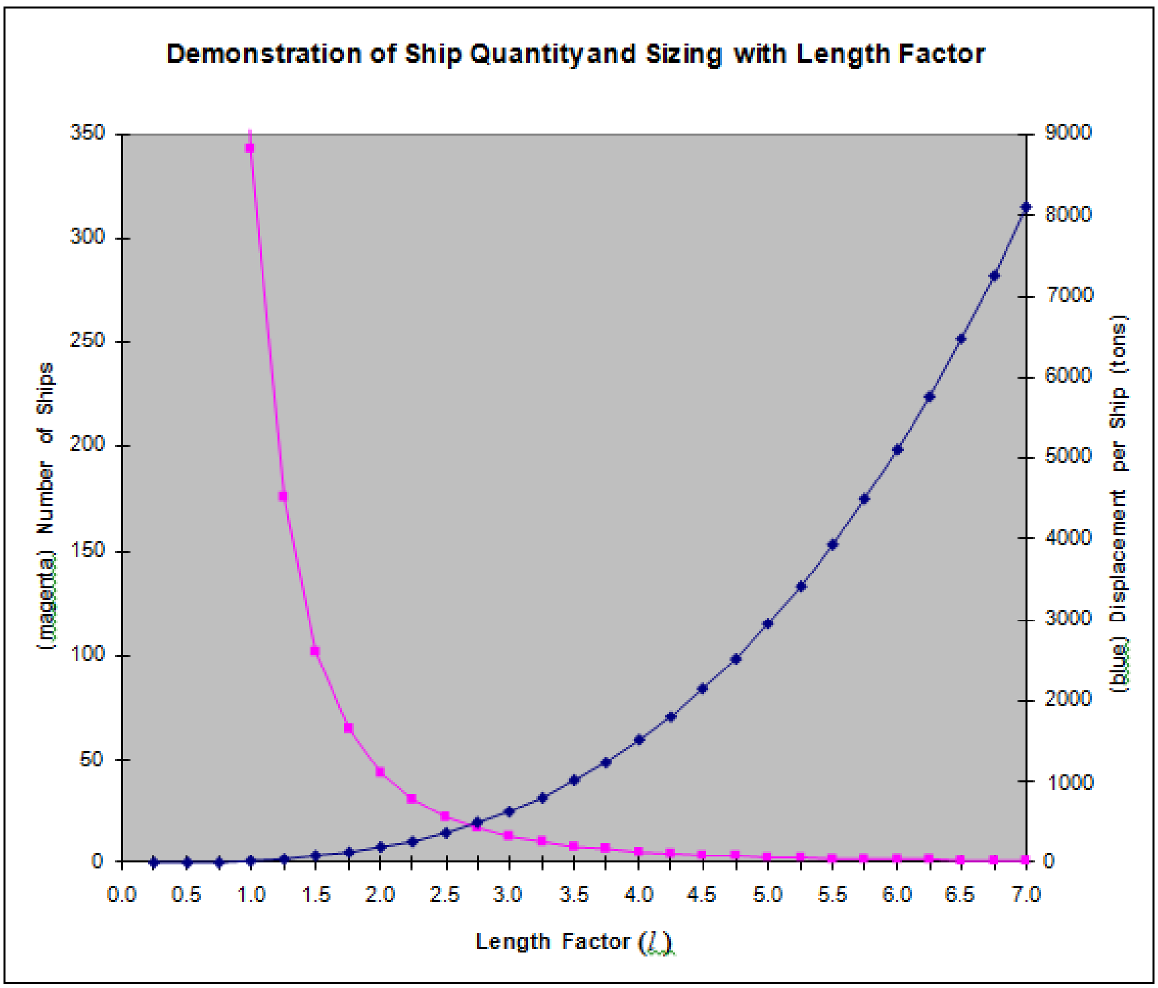

Figure 3. Ship Quantity and Displacement vs. Length Factor (From Sumsion 2008)

3. Minefield Density and Risk Considerations

Obviously, some minefields will be more risky to traverse than others. Therefore, a variety of minefield densities were modeled to show the impact on minefield density with optimum length factor. Several assumptions were made considering the size and type of minefield to introduce risk to the throughput analysis. These assumptions were provided by Sumsion in Table 1.

Assumptions for Minefield Geometry and Sizing	
Lethal radius of mines:	54.68 yards (50 meters) [9]
Width of channel:	2025.33 yards (1 nautical mile)
Low density minefield:	10 mines
Intermediate density minefield:	50 mines
High density minefield	250 mines

Table 1. Minefield Sizing Assumptions (From Sumsion 2008)

These assumptions were created in order to give a prediction of a generalized geography with various densities. The Uncountered Minefield Planning Model (UMPM) disperses the mines equally in the given lethal area. UMPM makes the assumption that the ship transits directly through the middle of the lethal area for the entire length of the minefield. In determining minefield density, the only significant factor to consider is the number of mines and the width of the minefield. The low, intermediate, and hight minefield threat densities are numerically defined above in Table 1 and are graphically shown below in Figure 4. As can be inferred in the figure, as the number of ships transiting an area increase, the probability of each ship becoming hit decreases (Sumsion 2008).

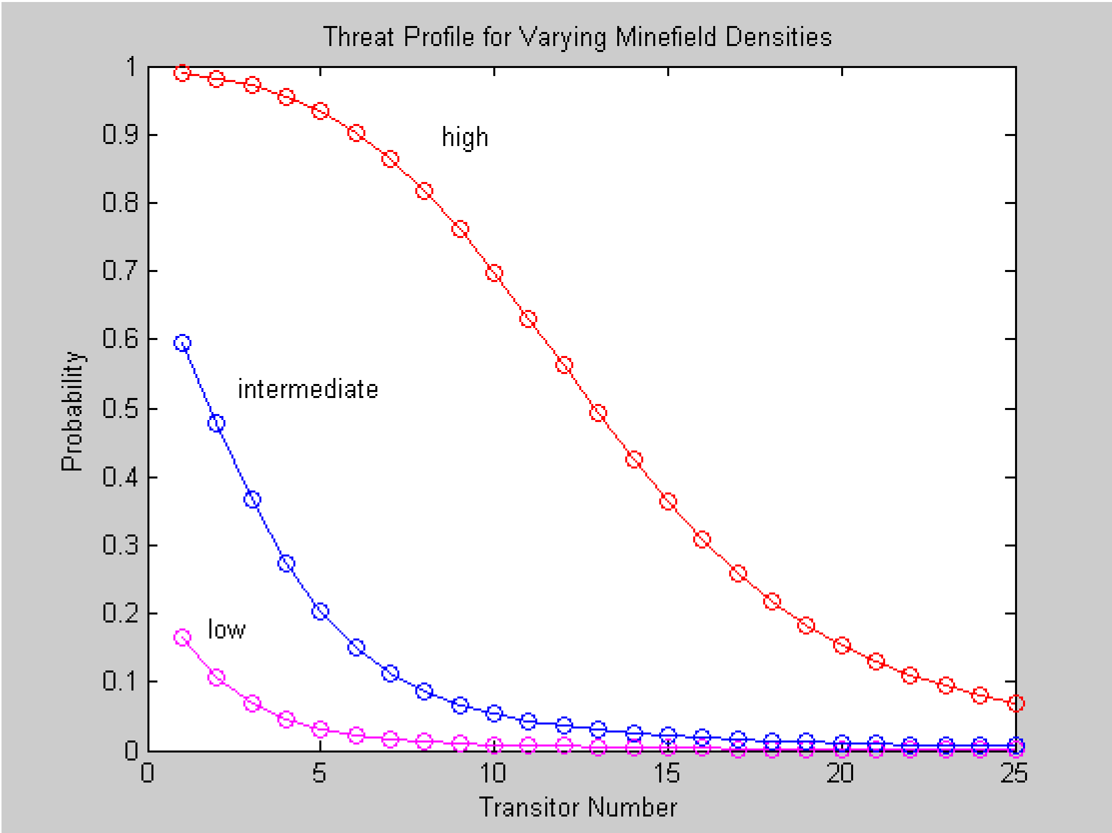

Figure 4. Threat profile of Varying Minefield Densities (From Sumsion, 2008)

4. Examples of Throughput Curves with and without Risk

One can infer that throughput should increase as the length factor of the ship increases. For this comparison, the total displacement for all ships of a certain length factor must be held constant. Graphing of throughput vs. length factor and fuel consumption vs. length is shown in Figure 5. As one can see, it takes many more ships of a smaller length factor to match up with one ship with a large length factor. This figure shows that as length factor increases, throughput in units of tons per hour increases. The red line demonstrates that a higher length factor (*l*) will be more fuel efficient and therefore will move cargo more efficiency. With less fuel needed onboard, more room will be available for cargo, obtaining a higher amount of throughput.

Therefore, a few large ships will be more efficient when compared against many small ships, since small ships use a lot more fuel in relation to larger ships (Sumsion 2008).

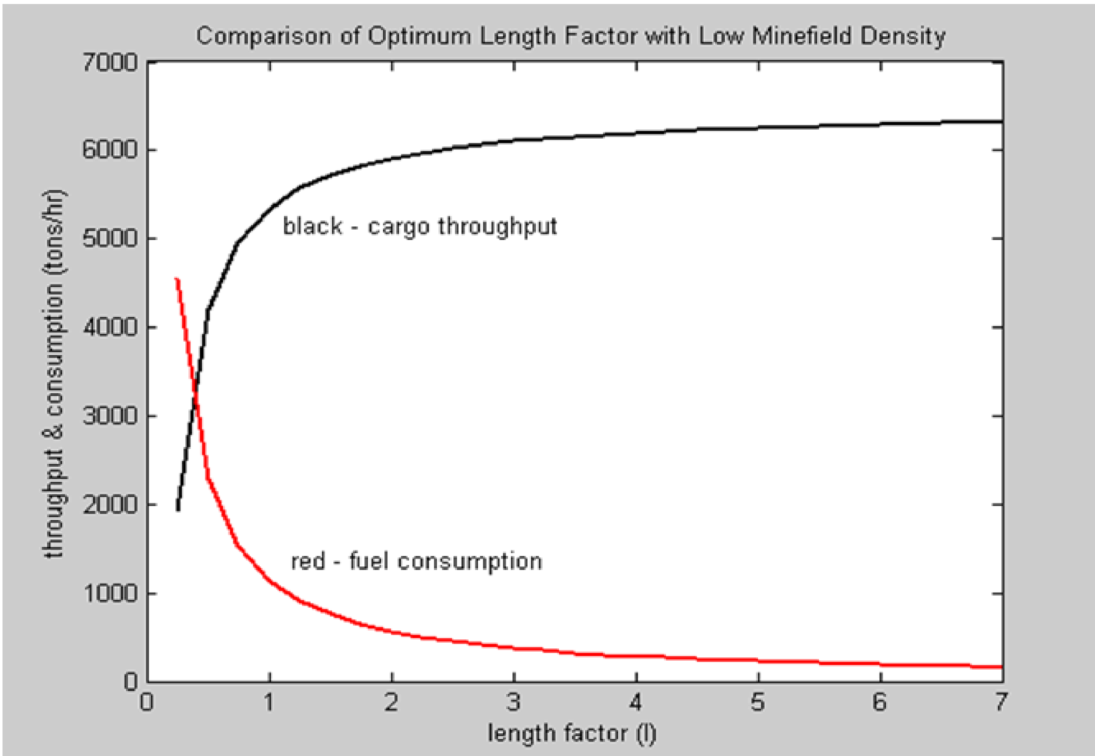

Figure 5. Throughput and Fuel Consumption vs. Length Factor (From Sumsion, 2008)

Once risk and survivability are considered, however, the curves will take a different shape. In this case with survivability and risk, many ships will actually be preferred to a few ships. It will be more challenging to sink a larger number of smaller ships. Now, the challenge becomes finding an optimized throughput when faced with a hostile risk (Sumsion 2008).

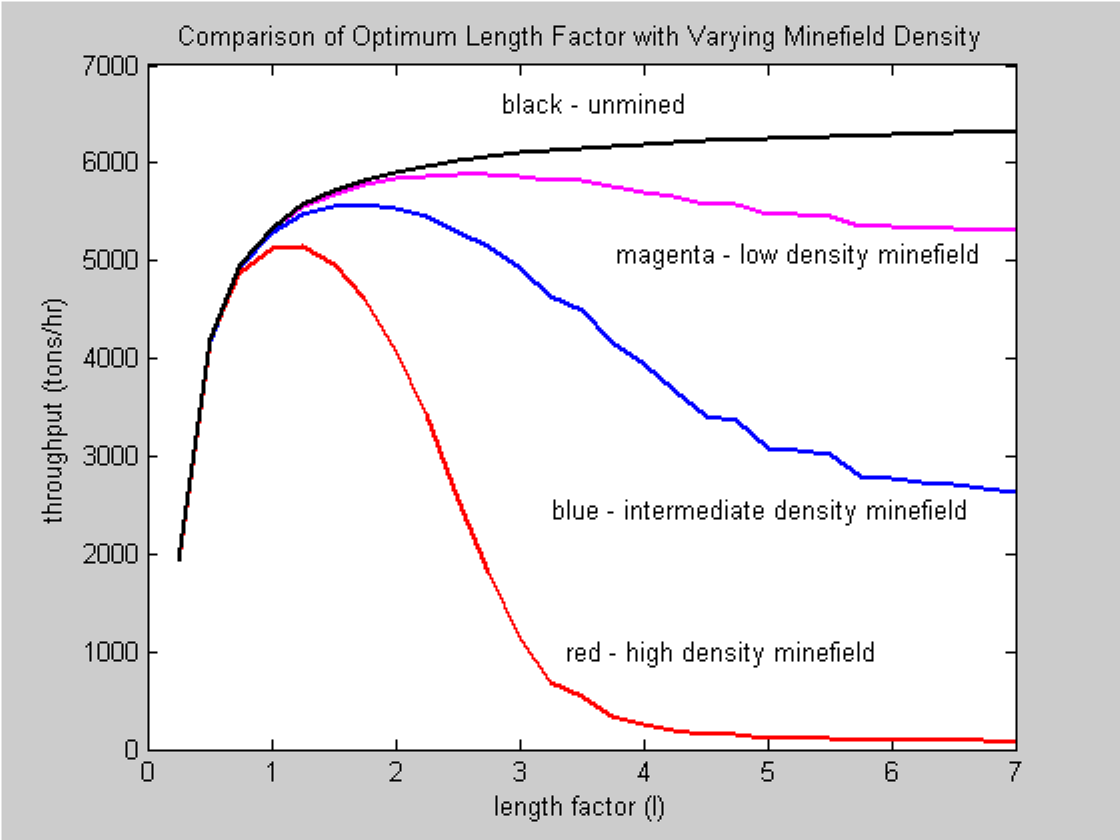

Figure 6. Throughput and Varying Minefield Densities vs. Length Factor (From Sumsion, 2008)

Figure 6 portrays the integration of the UMPM model into throughput curves for minefields in areas of varying lethal densities. This figure gives the graphical representation of how a small amount of larger ships is not always the best method in achieving maximum throughput. Length factors between1 and 3 for the varying density of the minefields were found to produce optimum amounts of throughput. Exact peak values for this figure are shown below in Table 2 (Sumsion 2008).

Minefield Density		
low	**intermediate**	**high**
2.75	1.75	1.25

Table 2. Numerical Values of Optimum Length Factors (From Sumsion, 2008)

For the example above, the parameters were defined as: LF = 80%, speed = 30 knots, range = 30 nm, SFC = 0.80 lb/hr/HP. In the following comparisons, each of these parameters (LF, speed, range, and SFC) will be varied to show the impact on optimum length factor. As previously demonstrated, adding risk to the throughput analysis yields curves to show expected throughput. To further understand the optimum operating values, other parameters were manipulated to see the impact on the optimum length factor. Parameters such as loading factor (LF), range, speed, and specific fuel consumption (SFC) were varied. The following figures demonstrate what happens to the optimum operating point as these conditions are changed (Sumsion 2008).

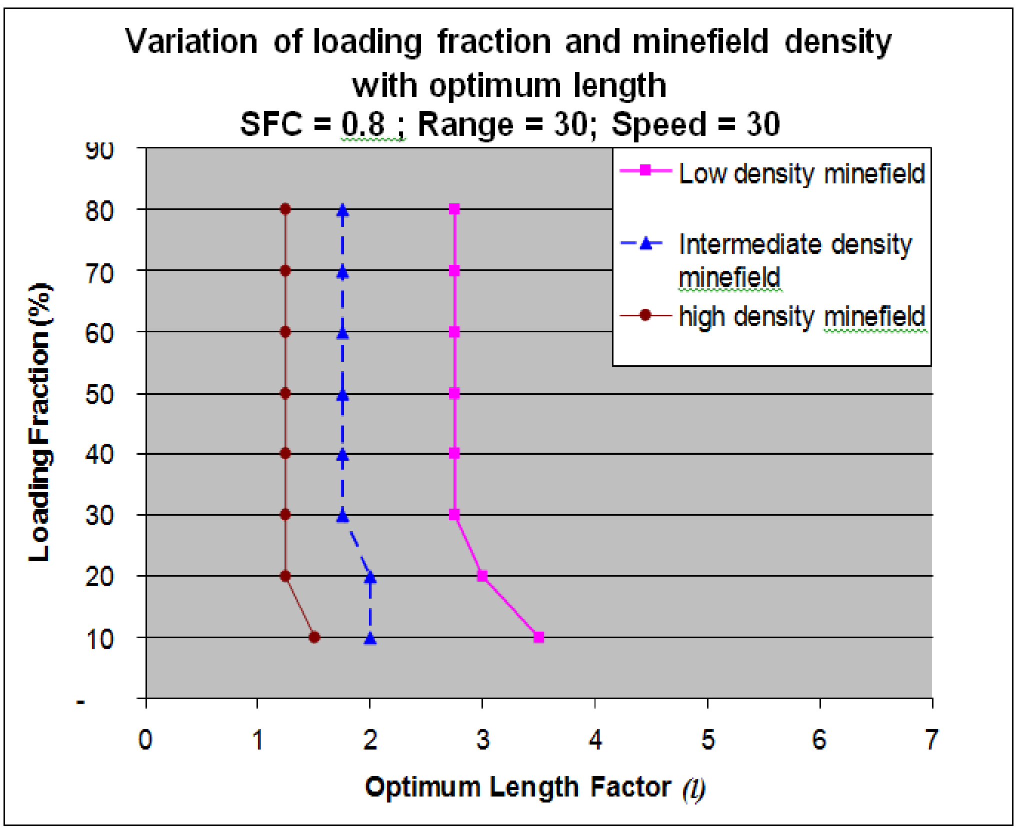

Figure 7. Loading Fraction and Minefield Density Variation vs. Optimum Length (From Sumsion, 2008)

Figure7 shows that loading fraction has nearly no impact on the optimum length factor until the loading fraction is below 30 percent.

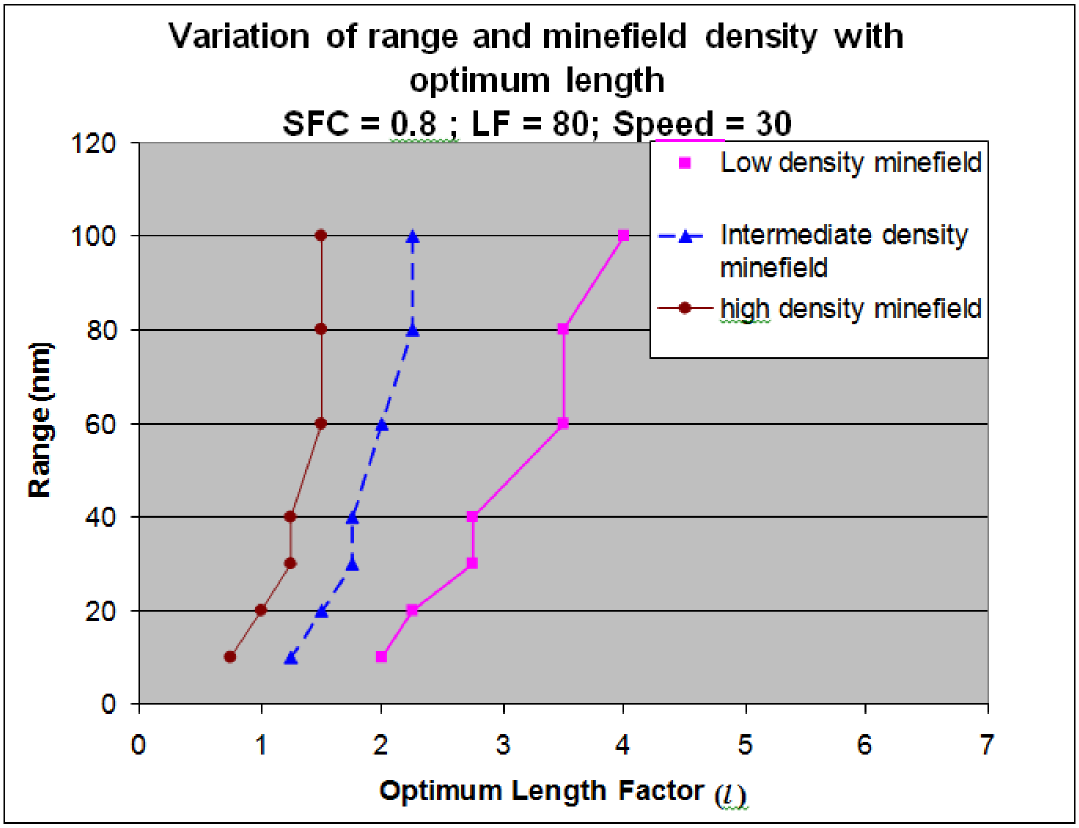

Figure 8. Variation of Range and Minefield Density vs. Optimum Length Factor (From Sumsion, 2008)

Range has a much more drastic impact than did loading fraction. As range increases, so does the optimum length factor. This is due to the increase in fuel with range. As fuel increases, available payload decreases. This pushes the curves to the right as shown in Figure 8.

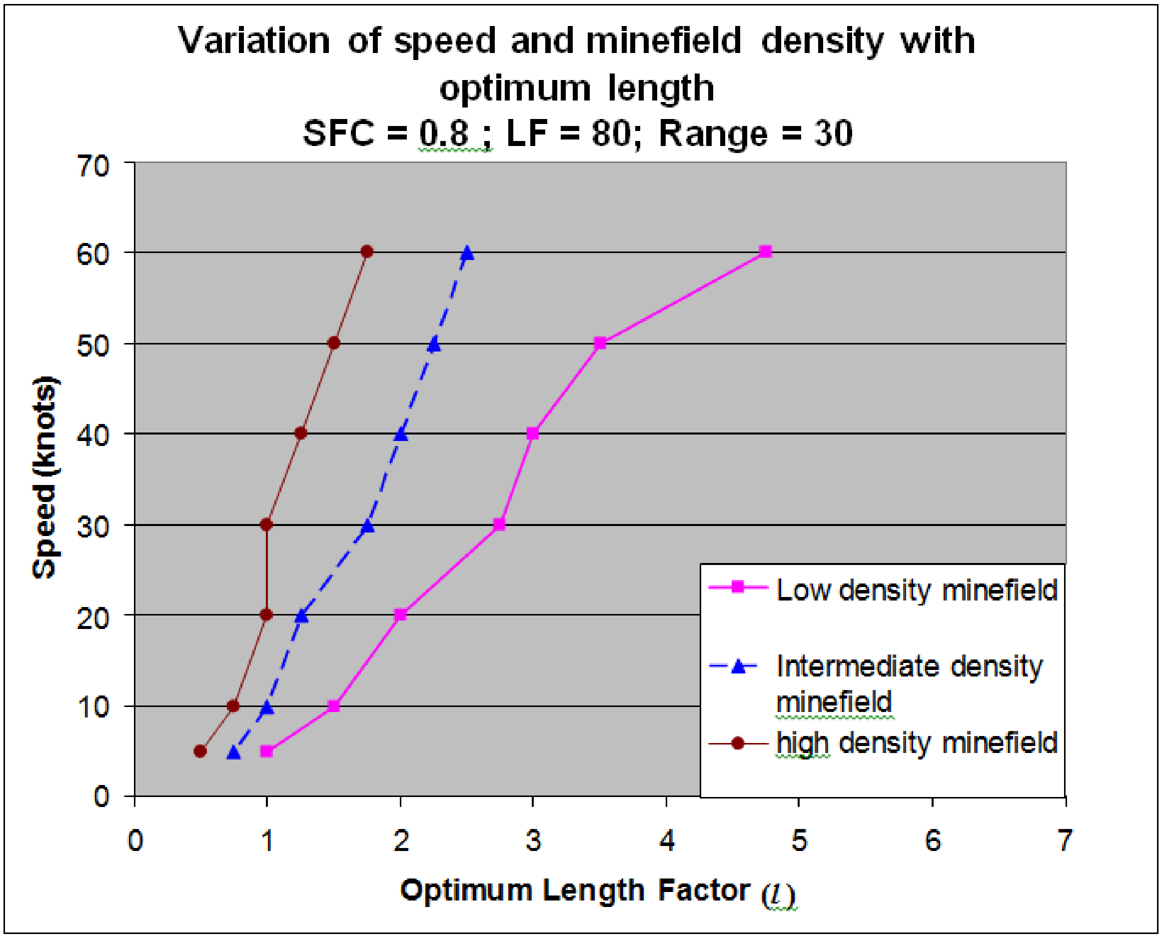

Figure 9. Variation of Speed and Minefield Density vs. Optimum Length Factor (From Sumsion, 2008)

Speed has a similar impact on length factor as range, as shown in Figure 9. A higher speed requires much more fuel. Speeds in excess of 20 knots drastically increase the length factor since the additional fuel load to maintain such speeds is high. This is even more difficult for the smaller vessels since a larger fraction of the remaining displacement must be dedicated to fuel. This pushes the optimum length factor higher with additional fuel loading. The optimum values vary most drastically with speed (Sumsion 2008).

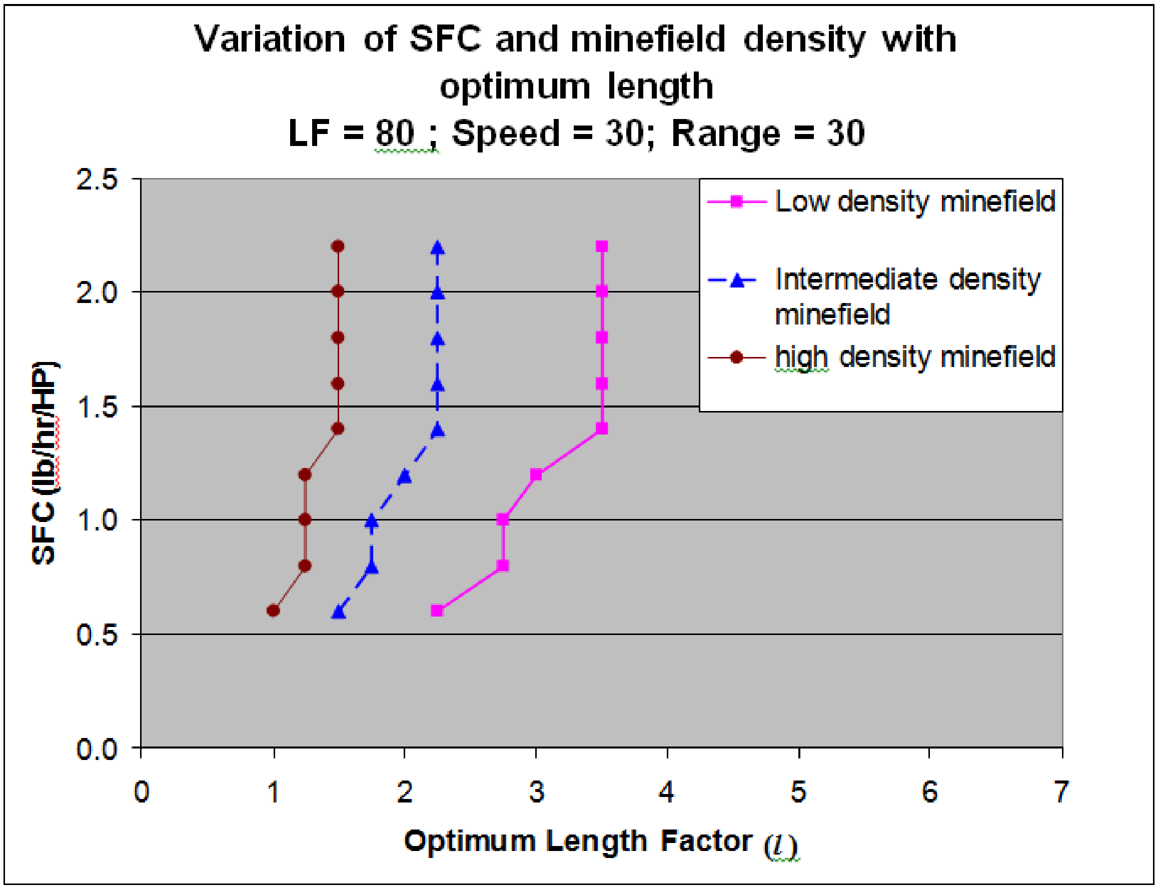

Figure 10. Variation of SFC and Minefield Density vs. Optimum Length Factor (From Sumsion, 2008)

Figure 10 shows that increasing SFC increases optimum length factor. As before, the increase in fuel loading also decreases the available payload of cargo. It is important to note that the increase is not as large for SFC as it is for speed or range. This is because SFC scales nearly linearly while speed and range do not (Sumsion 2008).

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II. MOTIVATION AND PROBLEM STATEMENT

A. SUSTAINMENT OPERATIONS AND SURVIVABILITY CONSIDERATIONS

Force sustainment operations are an integral part of the Navy. The Military Sealift Command's (MSC) sealift programs provide superior, efficient and cost-effective ocean transportation for the Department of Defense during both times of peace and war. More than 90 percent of the military's equipment and supplies are delivered to United States war fighters' by sea under the care of MSC (Military Sealift Command n.d.). Military Sealift Command currently operates around 115 non-combatant, civilian-crewed ships throughout the world. Additionally, the MSC has access to 50 other ships that are kept in reserve operation to be used only if severely needed (Sealift n.d.). Among these many ships are crane, container, hospital, and heavy lift ships that are all prepared with a variety of specialized equipment suiting their ship designation and making delivery of its cargo more efficient (Ship Inventory 2005). The technology of these cargo supply platforms used in delivery techniques have been crucial in supplying our warfighters with the tools they need to run successful missions.

It may be hypothesized that it is more beneficial for the U.S. Navy to more fully diversify their inventory of cargo ships to smaller, cheaper, and more numerous sea craft that would provide more opportunities to maximize throughput of cargo. It is commonly believed that the larger a ship is, the more efficiently it can transport throughput to an area. This thought process would be absolutely accurate if risk wasn't a main threat to U.S Naval forces. With the incorporation of attack analysis on these large cargo ships, the optimization of throughput is discovered to vary and be better achieved when a full analysis is done and a plethora of ship conditions are taken into consideration. When taking risk into consideration, it may then be more likely that more numerous and smaller cargo ships carrying a diverse combination of supplies would be more beneficial. In this strategy, if a successful attack happens to occur and damage a group of cargo ships, there will be other ships in transportation that may still survive to deliver the rest of the needed supplies to our troops (Sumsion 2008).

In order to have a highly efficient and effective power projection in a given area, we must ensure a highly successful supply of resources. In order to minimize the increased risk from hostile forces, the survivability of supply vehicles must be analyzed in force sustainment operations to determine the success rate of these supplies being delivered (Sumsion 2008).

B. RISK MANAGEMENT

1. Risk Analysis

Any attacks on vulnerable supply lines could be detrimental to forward deployed troops. There is an increased risk from unpredictable and changing hostile environments. Mitigation techniques must be employed to help prevent these types of attacks and attempts must be made to minimize risk through survivability enhancements (Sumsion 2008).

The littorals will give the largest benefit for diminishing risks to cargo supply. The most fail safe ways to limit and lower loss of human life in case of an attack would be to implement the use of autonomous vehicles. The use of these autonomous vehicles will help in advancing the overreaching goal of this research to maximize throughput while minimizing threat to human life (Sumsion 2008).

2. Autonomous Vehicles Utilization in Risk Reduction

Autonomous systems have allowed for aerial patrol of a hostile area with no threat to operator life. Our use of these systems in this analysis would consider autonomous water supply vehicles as minimizing potential risk to human life. Because an autonomous vehicle requires no local human control, they offer the potential to drastically reduce the risk to human life in hostile environments. These vehicles can either be controlled remotely from an outside source or by programming in coordinate geographic markers into the vehicle that the craft will maneuver through. Removing humans from the local operating area of the vehicle will introduce several advantages and disadvantages (Sumsion 2008).

Advantages of autonomous systems

1) Reduces risk to human life

2) Can enter environments that are dangerous to human life

3) More maneuverable

4) Longer endurance

5) Relatively inexpensive in comparison with manned ship (David Glade, 2000)

Disadvantages of autonomous systems:

1) Large bandwidth needed for communications

2) Low survivability in military operations

3) Current generation relatively expensive to develop and build

4) Cannot supplement human ship driver's senses, which make critical decisions about the use of lethal force (David Glade, 2000)

In many scenarios large cargo ships are unable to approach littoral coastal areas due to their large size and maneuverability limitations. Large ships may draft too much and risk high susceptibility when going within the dangerous firing range of costal shores. Additionally, minefields prevent these ships from closer approach. Instead of risking the crew of the large ship in this hostile environment, the ship has the option of deploying one or several autonomous vessels. Even these small vessels can encounter several threats while navigating to the shore, but since they are either operated by the large ship or programmed autonomously, there will be very minimal threat to human life (Sumsion 2008).

C. PROBLEM STATEMENT

The previous studies by Yeh demonstrated the usefulness of a relatively simple model to predict fundamental characteristics and properties of payload throughput tradeoffs. Such metamodels are particularly useful in the conceptual design phase where a very large number of design points are needed in order to properly cover as much of the tradeoff space as possible.

Sumsion's work in risk demonstrated that risk can have a significant effect on the expected value of payload delivery rates. However, Sumsion's work was restricted to a specific type of risk and the results were numerically produced for that model only. Therefore, it is difficult to generalize them under a broader definition of risk. Similarly, Yeh's results were obtained for a specific geometric shape that bears little resemblance with current ships. Overcoming these two deficiencies is precisely the scope of this work. We want to create a model for payload delivery through a region of risk that is general enough to be applicable to most ship types. At the same time, we want the model to have enough flexibility so that it can properly guide multiple design space explorations.

1. **Create a model to:**
   - Model to combing risk and payload considerations

2. **Model must be:**
   - Simple enough to apply in early stages of decision making where many parameters are not yet known
   - Generic enough to apply to as many scenarios and areas of operation as possible

III. THEORETICAL STUDIES

A. INTRODUCTION

The purpose of this chapter is to develop the framework for the theoretical studies involving cargo throughput and risk analysis. We will establish the basic risk environment and the fundamental formulas that relate probability of survival in the given environment to cargo ship throughput in later chapters.

There are many risks that shipping vessels can encounter while crossing a certain area. There are always prominent threats on the water such as sea mines, strikes from enemy ships, and pirate attacks. Sea mines have been the most relevant threat to cargo shipping and have been the most modeled source of risk. Sea mines are typically very simple in the way in which they operate. They merely stay where they are placed and wait to detonate when activated from a source that is traversing the area. This mine characteristic allows for a much easier mathematical representation. Other risk sources are more complicated to model, since they require many more deterministic variables.

Since the survivability of a ship traversing a minefield is the issue discussed, the risk portion of the discussion could be advanced to nearly any hostile risk. Though the models presented throughout the past have been substantially for sea mines, it is reasonable to assume any other hostile risk may be modeled as mines as well. Given certain parameters for loss rates and weapon density, this model can possibly be expanded to give a mathematical and statistical representation for any threat scenario.

The fundamental nature of the model developed in this work is to simulate a generic risk area in the path of a ship. When the ship enters this area of risk, it is assumed the ship gets hit and therefore killed. For the purposes of this study, mission completion is equivalent to avoiding the risk area. No prior knowledge of the risk area is assumed. In other words, no active risk avoidance procedures are established in place. This risk area may, under suitable modifications, represent a natural risk area due to shallow waters, an enemy activity area due to aerial bombardment or artillery, or a minefield of either contact or magnetic mines with a certain radius of influence.

B. SINGLE SHIP

If we are to have a given ship traveling in a designated area where there is a field of general risk, we need to determine the probability of hit and survival of the given ship traversing through the lethal area. In order to perform this derivation, we must first analyze the different components of the designated lethal area. Figure 11 portrays a schematic of the designated lethal area with one traversing ship.

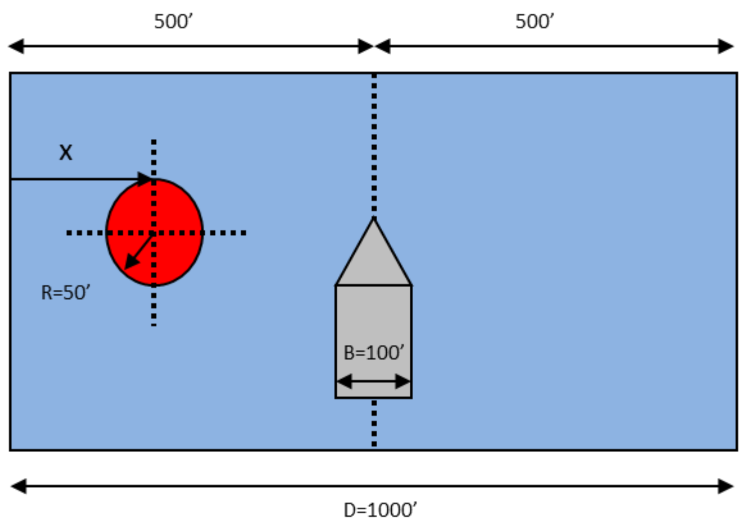

Figure 11. Ship's Area of Travel (After Driels, 2004)

In the given field we have a circular area of risk represented by its radius 'R'. Additionally, we have the total operational area's width represented by 'D' and the ship's beam represented by 'B.' This study assumes the ship is at the midpoint of the designated area. It should be mentioned that 'B,' in reality, may not be identical to the ship's actual beam, as it is closely related to the overall path deviation port to starboard. The distance of the left bank to the center lethal area is represented by 'x.' From Figure 11 above, we can see that the ship will be damaged when 'x' satisfies the following equation:

$$\frac{D}{2}-\frac{B}{2}-R<x<\frac{D}{2}+\frac{B}{2}+R \qquad (1)$$

In this case we would have a probability of damage of $P_H = 1$. For values of 'x' not satisfying this equation, the probability of damage is zero and the ship is assumed to complete its mission successfully.

If we assume that 'x' is a random variable with a uniform distribution, we can calculate the expected value of probability of damage for a large number of samples. To get the calculated probability of damage in any ship-risk-area, we will need to analyze the following integral that takes into consideration the upper and lower bound of the ship's given area. Equation 2 will determine the probability of only one ship becoming hit.

$$\int_{-\infty}^{+\infty} P_H(x)dx = \int_{x_{\min}}^{x_{\max}} \frac{1}{D} dx \tag{2}$$

In Equation 2, xmin and xmax, are the minimum and maximum values of 'x' as determined in Equation 1. Equation 3 is then the further simplified notation to find the actual probability of becoming hit.

$$P_H = \frac{1}{D}\left(B + 2R\right) \tag{3}$$

Therefore, the probability of survival would be one minus this probability of hit.

$$P_s = 1 - P_H = 1 - \frac{1}{D}(B + 2R) \tag{4}$$

To further simplify these two equations we can introduce dimensional variables based on the ratios of the ship's beam and radius of the risk area.

$$\frac{R}{D} = r \text{ and } \frac{B}{D} = b \tag{5}$$

In essence, 'r' is a measure of the density of the risk area, so a larger 'r' will correspond to a more lethal environment. Similarly, 'b' is a measure of ship size for a given area.

Our probability of hit and survival equations will now become much simpler.

$$P_H = b + 2r \tag{6}$$

$$P_S = 1 - b - 2r \tag{7}$$

C. TWO SHIPS

Now, given two independent ships in their designated lethal areas, the probability of damage and survival will be dependent on each ship's respective size. However, for reasons of simplification we will assume that all the ships will have the same base width. Therefore, the base probability of any ship traversing an area of risk will be the same. In addition, we assume that there is no information exchange between the two ships. In other words, if one gets hit the other will not employ evasive actions. Therefore, the two events are independent. Furthermore, we assume that the area of risk remains intact after collision with each ship. This, in essence, limits the types of risk that the equations can model, but provides a solid starting point for the calculations and the actual model development. So, the independent probabilities of one ship getting damaged will be equal to the second ship getting damaged as shown in Equations 8 and 9 below.

$$P_{1H} = b + 2r, P_{1S} = 1 - b - 2r \tag{8}$$

$$P_{H2} = b + 2r, P_{S2} = 1 - b - 2r \tag{9}$$

The dimensions shown in Figure 11 above will have an outcome probability of damage and survival as follows in their respective order.

$$\frac{B}{D} = \frac{100'}{1000'} = \frac{1}{10} = 0.1 = b \quad \text{and} \quad \frac{R}{D} = \frac{50'}{1000'} = 0.05 = r$$

$$P_H = b + 2r = 0.1 + 2 \times .05 = 0.2$$

$$P_S = 1 - b - 2r = 1 - 0.1 - 2 \times 0.05 = 0.8$$

The probability of both ships surviving will be the probability of survival of each ship multiplied by each other as shown in Equation (10):

$$P_{2S} = (P_{s1})(P_{s2}) = (1 - b - 2r)(1 - b - 2r) = (1 - b - 2r)^2 \tag{10}$$

The probability that both get damaged is portrayed in Equation 11:

$$P_{2H} = (P_{H1})(P_{H2}) = (b + 2r)(b + 2r) = (b + 2r)^2 \tag{11}$$

The probability at least one ship gets hit is shown in Equation (12):

$$P_{1H,or\,2H} = (1 - P_{S1,2}) \tag{12}$$

The probability that one ship gets damaged is equal to the probability of at least one ship getting hit minus the probability of both ships getting hit, as demonstrated below in Equation 13.

$$P_{1H} = \left(1 - P_{s1,2}\right) - \left(P_{H1,2}\right) \tag{13}$$

Inserting and simplifying the equations above produces the following result for a one hit, one survival case:

$$P_{1S} = P_S P_H = (1 - b - 2r)\square(b + 2r) = -2b^2 - 8br + 2b - 8r^2 + 4r \tag{14}$$

1. Two Ship Summary

In summary we have developed the following formulas:

- Probability of two ships surviving (Equation 10):

$P_{2S} = (P_{S1})(P_{S2}) = (1-b-2r)(1-b-2r) = (1-b-2r)^2$

- Probability of one ship surviving (Equation 14):

$P_{1S} = P_S P_H = (1-b-2r)(b+2r) = -2b^2 - 8br + 2b - 8r^2 + 4r$

- Probability of zero ships surviving (Equation 11)

$P_{0S} = (P_{H1})(P_{H2}) = (b+2r)(b+2r) = (b+2r)^2$

2. Numerical Example

By using the parameters of Figure 11 as an example, we get the following results for a two ship case:

- Probability of two ships surviving:

$P_{2S} = (1-b-2r)^2 = (1-0.1-2*0.05)^2 = 0.8^2 = 0.64$

- Probability of one ship surviving:

$P_{1S} = -2b^2 - 8br + 2b - 8r^2 + 4r = -2*0.1^2 - 8*0.1*0.05 + 2*0.1 - 8*0.05^2 + 4*0.05 = 0.32$

- Probability of zero ships surviving:

$P_{0S} = (b+2r)^2 = (0.1+2*0.05)^2 = 0.2^2 = 0.04$

3. Probability Tree

One can also determine the correct probability equations to predict an outcome in a certain scenario by constructing what is known as a “kill tree diagram.” A kill tree diagram is a graphical tool that breaks down and maps out all of the components of a specific scenario. The kill tree diagram begins with a single entry point that in the use of our research has two paths or branches leading out from it. Each of these branches can then subdivide into two more branches. This process is repeated until all possible outcomes of a specific event are represented (Tree Diagram n.d.)

To make this diagram, one must start out by creating two branches of one ship’s probability of hit and survival, stemming out from one point that represents the first ship. For each new ship that is added to the scenario, another level will be added to the diagram by stemming two new branches of hit and survival outcomes from each previous set of hit and survival results. When looking at the final resulting level, one will notice a mixture of outcomes including the possibilities of getting all hits, all survivals, and combinations of both. When looking for the outcome of a certain instance, one must find the outcome they are looking for on the bottom level of the kill tree that corresponds to the desired number of ships traversing a lethal area. Then, one must trace all the roots back up to the very top of the tree and multiply these ‘roots’ together. Then, one must multiply this answer by the number of occurrences that occur for the same specific probability scenario they are looking for. For instance, in the two ship scenario, there are three combinations of scenarios that may occur. All of the ships will survive, none of them will survive, or just one will survive. Say a student wants to find the probably that one of the ships survives out of the two that are crossing the lethal area. The student must look at the bottom layer of the kill tree diagram and determine that there are two instances of having a one ship survival outcome in a two ship case. These two cases are designated by the color orange in the diagram below. Either the first ship survives and the second ship gets hit, or the first ship gets hit and the second ship survives. Applying the same numbers as computed above for ‘r’ and ‘b’, we get the following kill tree diagram and the same results predicted in our earlier process above. For example all the possible outcomes of hit and survival of two given ships is shown in Figure 12.

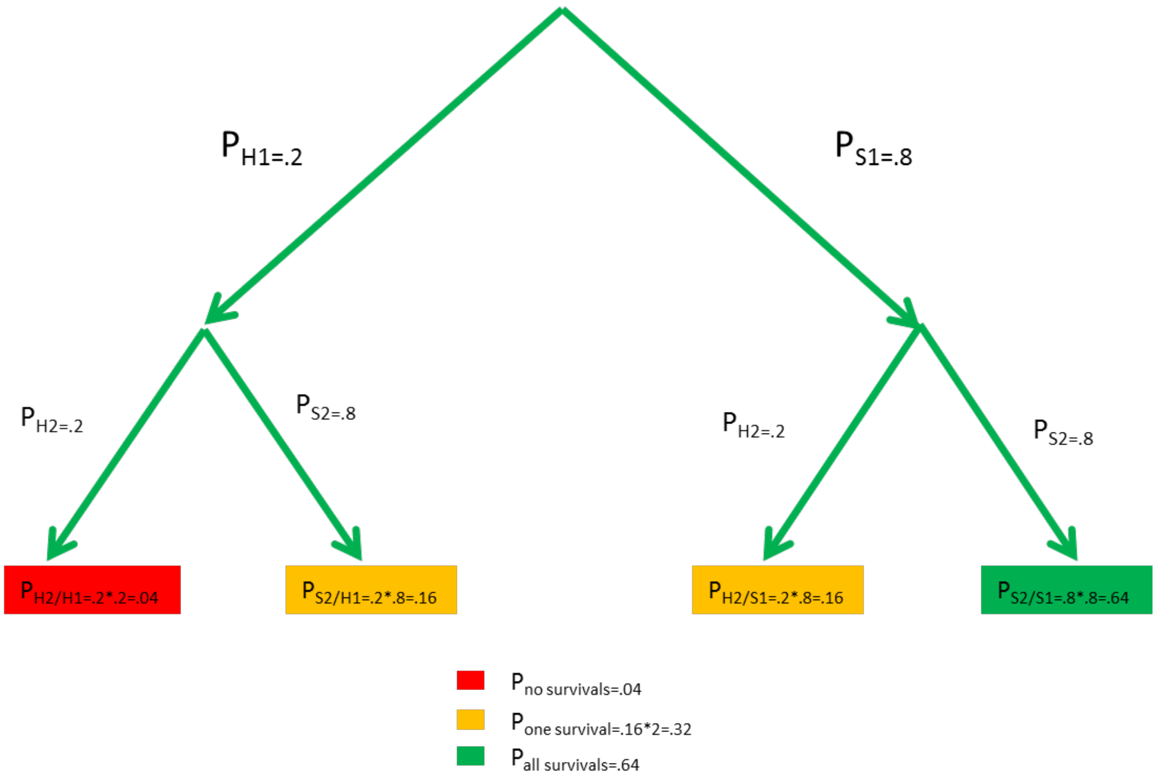

Figure 12. Kill Tree for Two Ships Traversing a Lethal Area

$$P_{S2/H1} = 2(1-b-2r)^1(b+2r)^1 = 2(1-.01-2\times 0.05)^1(.01+2\times 0.05)^1 = 2(0.8\times 0.2) = 0.32$$

D. MULTIPLE SHIPS

With any number of given ships, one can use the kill tree diagram approach to determine the probability of survival equations for any scenario. In the kill tree shown below in Figure 13, there are three ships traversing a lethal area. To determine the probability that all three ships get hit, one must look at the last row of the diagram with the green highlighted outcome of $P_{S1,S2,S3}$. By looking at the two above levels where the desired outcome originated from, one can determine the probability of survival of all three ships by multiplying the equations of P_{S1} , P_{S2}, and P_{S3} together. This will leave us with $P_S^{\,3}$. Since there is only one possible outcome of all three ships surviving, this equation doesn't need to be multiplied by any other number or reoccurrence. In the same way the probability of $P_{H1,H2,H3}$ would be $P^3{}_H$. If one wanted to find out the probability of a combination of both survival and hit, one would take the probability of hit equation, raise it to the number of ships that were hit and then multiply that answer by the probability of survival equation raised to the number of ships that survived. Once this is done, one would multiply this final value by the number of times that this same outcome occurs for the probability of outcomes of the three ships. For example, to find the probability of two ships getting hit and one surviving, one would have the result of $P_{2H,1S} = (P_H{}^2 P_S) \times 3$. The equation is multiplied by three because there are three instances where there are two hit ships and one surviving ship in the last layer of the kill tree diagram for the three ship case. These three cases are highlighted in orange in Figure 13. Table 3 provides a summary of the different probability equations for each outcome for a three ship case.

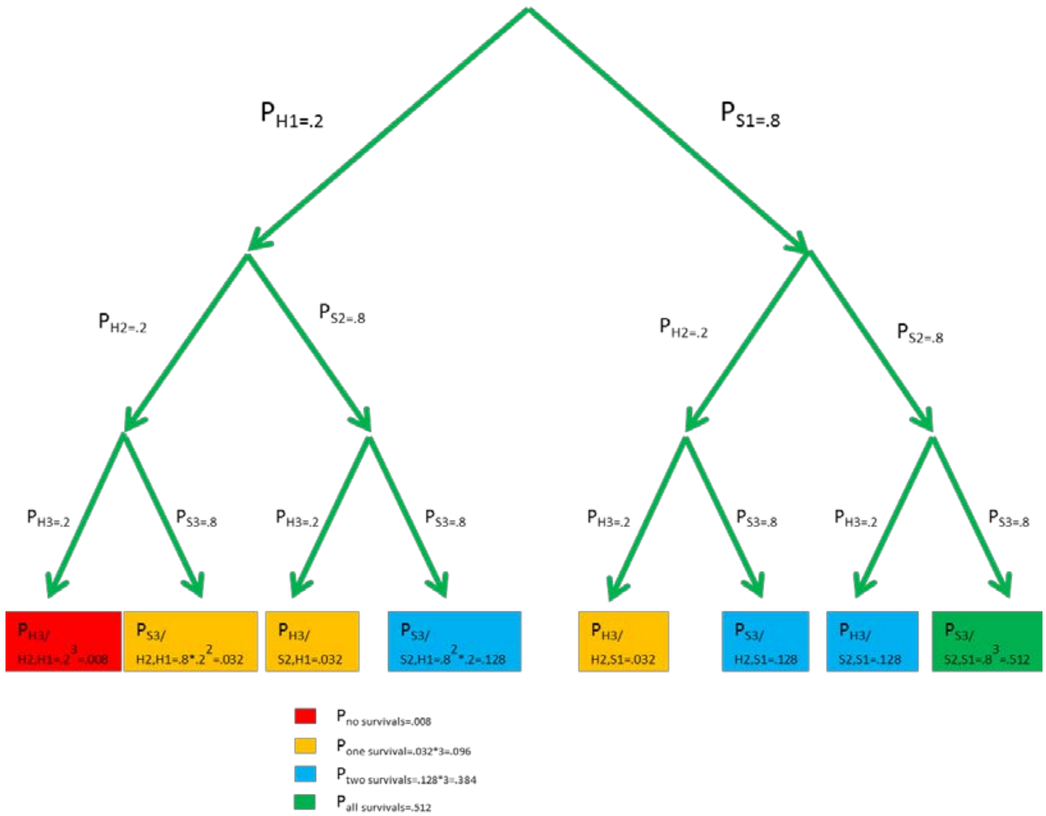

Figure 13. Kill tree for Three Ships Traversing a Lethal Area

Survival/Ships	1	2	3
0	$[(1-b-2r)^0(b+2r)^1]1$	$[(1-b-2r)^0(b+2r)^2]1$	$[(1-b-2r)^0(b+2r)^3]1$
1	$[(1-b-2r)^1(b+2r)^0]1$	$[(1-b-2r)^1(b+2r)^1]2$	$[(1-b-2r)^1(b+2r)^2]3$
2		$[(1-b-2r)^2(b+2r)^0]1$	$[(1-b-2r)^2(b+2r)^1]3$
3			$[(1-b-2r)^3(b+2r)^0]1$

Table 3. Probability Matrix Equations for One to Three Ships

$$P_{\#H,\#S} = [(1-b-2r)^{\#S}(b+2r)^{\#H}]N \tag{15}$$

S= #ships surviving
H= #ships getting hit
N=# same combinations in last layer of kill tree

Multiple Ships Summary

In summary we have developed the following formulas:

- Probability of three ships surviving:

$$P_{3S/0H} = (P_{S1})(P_{S2})(P_{3}) = (1-b-2r)(1-b-2r)(1-b-2r) = (1-b-2r)^3$$

- Probability of two ship surviving:

$$P_{2S/1H} = (1-b-2r)(1-b-2r)(b+2r) = (1-b-2r)^2(b+2r)^1$$

- Probability of one ship surviving:

$$P_{1S/2H} = (1-b-2r)(b+2r)(b+2r) = (1-b-2r)^1(b+2r)^2$$

- Probability of zero ships surviving:

$$P_{0S/3H} = (b+2r)(b+2r)(b+2r) = (b+2r)^3$$

IV. SIMULATIONS-BASED

A. INTRODUCTION

Modern U.S. warships are extremely intricate systems make analysis and modeling very difficult. Naval Architects are constantly in pursuit of developing new and improved models that replicate warship complexity. However, modeling and simulation of complex ship design doesn't always have to be such an intricate process of modeling. It has been found that a simple model, having as few as five parameters, can provide extremely valuable insights in the design process. In this chapter, we will demonstrate the use of what is known as the Very Simple Model (VSM) of ship design, which uses the Five-Parameter Method as its basis for model considerations. Once these parameters are explored they will be used in design to come up with criteria for potential solutions that will meet any given set of mission requirements that are desired (McKesson 2006).

B. FIVE-PARAMETERS

There are five major parameters that govern cargo carriage. The first parameter considers the amount of power required to navigate through the water, which depends on the vehicles' Lift/Drag ratio. For this parameter, the vehicle's highest total attainable lift to drag ratio is considered. The second parameter explained is propulsive efficiency. Fuel weight depends on the propulsive coefficient that is used to convert drag to power. For this parameter, one examines the highest propulsion efficiency that can be obtained. Ship weight is an important characteristic that specific fuel consumption (SFC) is dependent on. SFC is the third parameter to examine. Specific fuel consumption is used in the conversion of power to fuel weight. For this parameter, one examines the lowest fuel consumption attainable. The two parameters taken into consideration for light ship weight are weight of power and weight of cargo carriage. For these two parameters, one must analyze the lightest propelling machinery available, as well as the minimum weight of the ship's structure, crew, auxiliary systems, and other components which are needed for the carrying the cargo (McKesson 2006).

In using these five parameters, the procedure starts with the analysis of the ship's ratio of displacement to resistance (L/D), overall propulsive coefficient (OPC), and specific fuel consumption (SFC) to obtain weight of fuel. Then one must work to obtain the weights of machinery, cargo, and cargo carriage, to accumulate the weight of the fully loaded ship. Utilizing knowledge of the propulsive efficiency and specific fuel consumption, one can obtain how fast and how long the ship is capable of traveling.

1. First Parameter: Lift/Drag Ratios

The equation presented from previous research suggests that the ship resistance performance can be approximated as a function of volumetric Froude Number (Fn_{vol}) in the following equation.

$$\frac{L}{D} = 5 + 40Fn^{-3.0}{}_{vol} \tag{16}$$

This equation, along with a set of data points representing various ship types such as catamarans and monohulls is plotted in Figure 14. This figure is referred to as the "Best Practices Curve." This simple size and speed dependent equation allows one to estimate probable drag values a designated ship is capable of reaching. This best practices curve gives a close approximation of the system by approximating a certain length to drag ratio based on the ships volumetric Froude Number (McKesson, A Parametric Method for Characterizing the Design Space of High Speed Cargo Ships 2006).

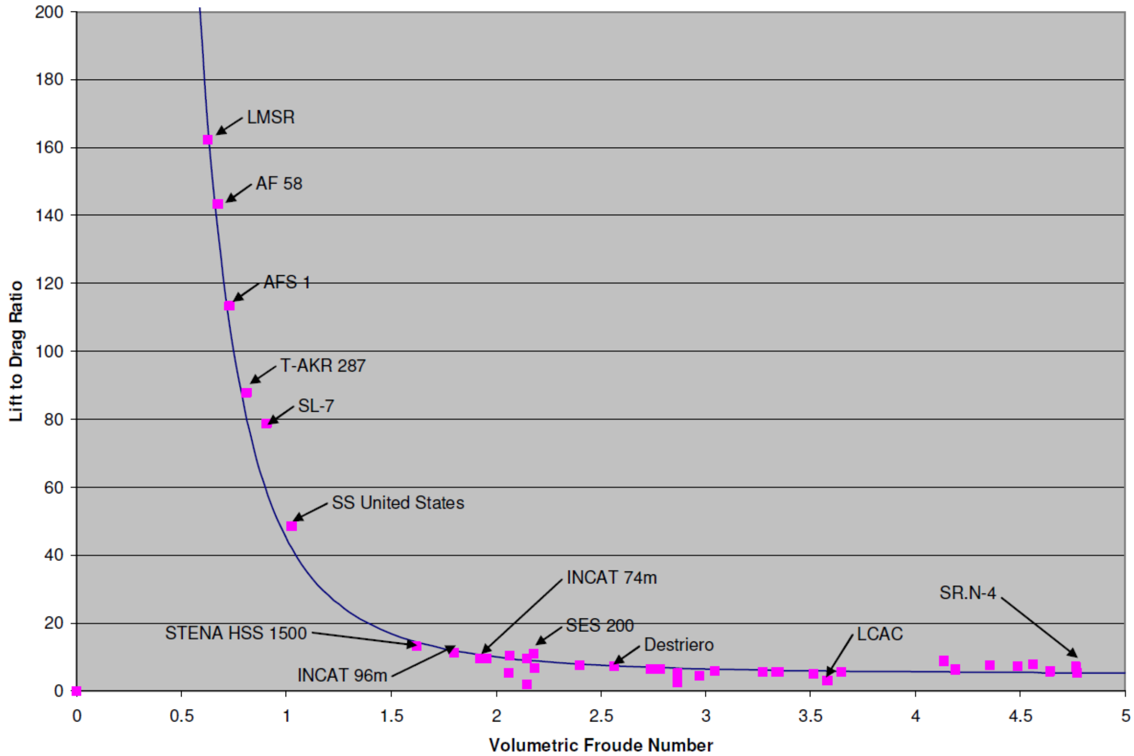

Figure 14. Best Practices Curve of Ship Lift/Drag Ratio (From McKesson, 2006)

2. Second Parameter: Propulsive Efficiency

The next big parameter to examine is propulsive efficiency, or weight of fuel. This weight is composed of propulsive efficiency of the ship and fuel efficiency of the power plant. OPC is defined as the ratio of Effective Power (EHP) divided by the total installed Shaft Horsepower (SHP) which is really using the installed Shaft Horsepower of the Maximum Continuous Range (MCR). Figure 15 portrays OPC values which suggest an OPC of around 0.6 for propellers and 0.7 for water jets (McKesson 2006).

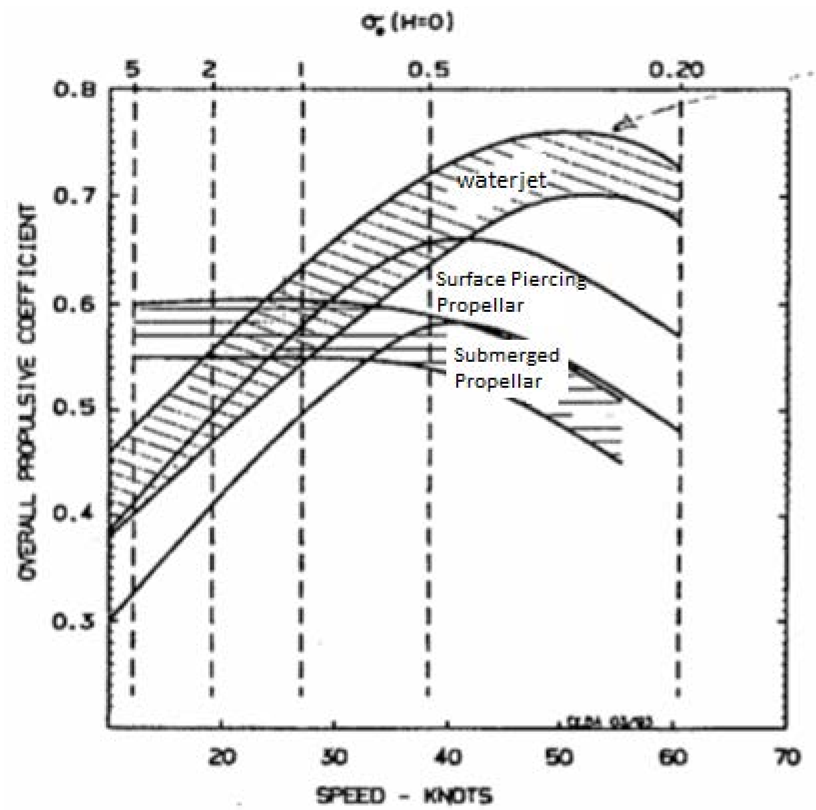

Figure 15. 1997 Limits of Overall Propulsive Coefficient (From McKesson, 2006)

3. Third Parameter: Fuel Rate

MCR will also be taken into account for specific fuel consumption (SFC) rates. Figures 16 and 17 depict some typical SFC data. Some reasonable SFC values have been found to lie between the range of 0.35–0.40 lbs./hp-hour (McKesson 2006).

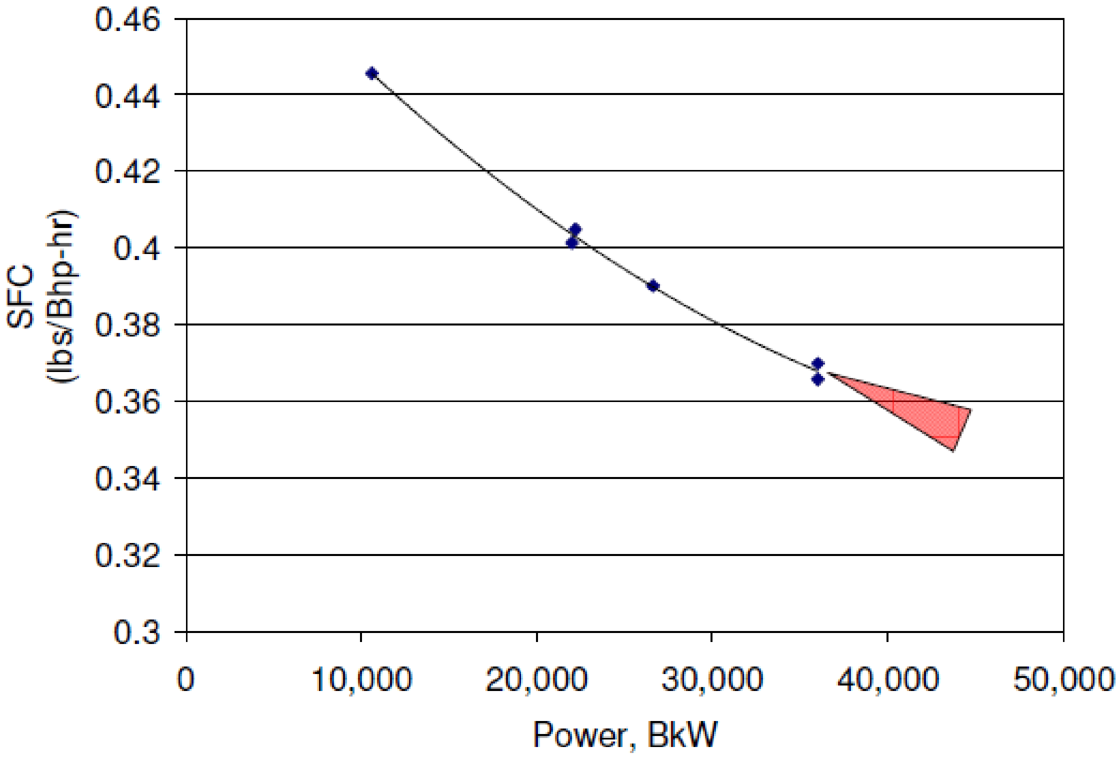

Figure 16. Propulsive Gas Turbines, SFC vs. Power, Current and Future Engines (From McKesson, 2006)

4. Fourth and Fifth Parameters: Weight of Power and Weight of Carriage

The final two parameters needed to utilize McKesson's parametric method are weight of power and weight of cargo carriage. These two parameters contribute to light ship weight. Weight of the propulsion plant, which includes the engines and propulsions are incorporated into the weight of power. The weight of cargo carriage is determined by the weight of the carrying device in which the cargo is placed. Weight of power will be presented in terms of lbs/hp and the cargo carriage multiplier will be presented in units of lbs/lb (McKesson 2006).

C. EXAMPLE

As an example, in 2005 the Office of Naval Research (ONR) tasked many suppliers with finding the feasibility of designing a ship that had the following requirements listed in Table 4:

ONR Requirements
3600 LT Cargo
43 knot speed
5000 nautical mile range

Table 4. ONR Design Requirements (From McKesson 2006)

The ship that was to meet these requirements had to be less than 560 ft. in length and less than 12,000 tons in displacement. For this research, we put together an excel spreadsheet that implemented the example of the five-parameter model in order to make a program that would be able to calculate the feasibility of designing a ship able to meet any given requested characteristic of cargo, speed, and range (McKesson, A Parametric Method for Characterizing the Design Space of High Speed Cargo Ships 2006).

1. The Five Parameters

a. Lift/Drag Ratio

Basic knowledge of ocean engineering informs us that the equation for Froude number is as follows:

$$Fn = \frac{V}{g * L} \tag{17}$$

Assuming a weight of 12,000 LT and a speed of 43 knots, we are able to calculate the Froude number based on velocity of the ship and volumetric length. Converting displacement in this case to a volumetric length of ship produces a value of 22.83m and a velocity of 22.12m/s. These values yield a Froude number of 1.478. The

Best Practices Curve equation suggests using a designed ship with a L/D value of 17.382. This means we will have a resultant resistance of 1546,427.07 lbs.

b. Propulsive Efficiency (Weight of fuel) & Fuel Rate

Using the values of resistance and speed, effective horsepower (EHP) is discerned to be 204,060.22 hp. Overall propulsive efficiency in this scenario is assumed to be .6. SHP is calculated from EHP and OPC resulting in a value of 340,100.37 hp. Fuel rate SFC is assumed to be a value of .4lbs/hp.-hr in this case. Based on the above values and assumptions fuel weight is calculated to be 7,061.88 LT. Displacement minus the fuel is equal to 4,938.12LT.

c. Weight of Power

For this scenario we will be assuming that for every unit of horsepower used, there will be an additional 10 lbs. of weight added to the weight of the ship to provide this power. These calculations will assume an additional 10 lbs. per horsepower are used to meet these design requirements. Therefore, we are able to determine that the weight of machinery is equivalent to approximately 1,518.31 LT. A weight of 3,419.81LT will still be available for cargo and cargo carriage.

d. Weight of Carriage

If the cargo carriage multiplier is 2lbs/lb., then this means that the 3,419.81 LT yields 2,279.87 LT of ‘ship’ or cargo carriage, plus an additional 1,139.94 LT of cargo. These results are far short of ONR’s goal.

2. Determining Length and Beam of the Vessel

From knowing just these five simple parameters one can determine the length and beam of the vessel that fits the criterion. To determine these lengths, I first constructed a table in excel shown in Table 5 of the length, beams, and displacements of various types of sailing vessels such as monohulls, catamarans, and surface effect ships (SES).

Ship Class	Actual Length (m)	Actual Beam Length (m)	Full Load Displacement (LT)	Volumetric Length (m)
Komandor class	88.30	13.60	2429.56	13.01
Cyclone class	54.56	7.62	378.93	7.00
National Security Cutter	127.41	16.46	4112.06	15.50
WMEC Famous class cutter	82.30	11.58	1791.25	11.75
Hamilton Class	115.21	13.11	3300.00	14.41
WMEC Reliance class cutter	64.01	10.36	1003.93	9.69
OPV (PSO)	90.50	13.50	2249.91	12.68
Krabi	90.50	13.50	2499.91	13.13
OPV (PSO)	80.01	13.01	1850.27	11.88
Kotor class	96.62	12.80	1870.00	11.92
PSO	98.45	13.11	2071.79	12.34
Dost class	88.70	12.19	1699.73	11.55
Meteoro class	93.88	14.33	2795.18	13.63
PSO	80.47	13.11	1695.81	11.54
Vikram class	74.07	11.28	1279.47	10.51
Vikram class	74.07	11.28	1224.38	10.35
Guaiqueri class	98.90	13.60	2333.57	12.84
River Class	79.75	13.60	1699.73	11.55
Modified River Class	81.66	13.60	1847.32	11.87
Alboran class	66.50	11.00	1963.48	12.12
Viana Do Castelo	83.10	12.89	1838.48	11.85
Diciotti class	53.40	8.10	392.68	7.09
Serviola class	68.58	10.36	1146.61	10.13
Langkawi class	75.00	10.80	1300.18	10.56
Milgem class	99.06	14.33	1999.91	12.19
Gowind corvette	87.00	13.00	1476.34	11.02
Florėal class	93.50	14.00	2949.65	13.88
Cassiopea class	79.80	11.80	1475.36	11.02
Asheville	50.10	7.30	235.27	5.97
Sentinel	46.70	7.70	353.30	6.84
Island	33.50	6.40	168.30	5.34
Valpas	48.49	8.50	545.27	7.91
OPV (PSO)	60.05	11.28	1377.86	10.77
Improved Tursas class	57.91	10.97	1100.36	9.99
Tursas class	61.57	10.06	1249.91	10.42
PBO	84.43	12.50	1823.75	11.82
PSO	43.59	8.50	260.80	6.18
Rani Abbakka class	51.21	8.41	274.55	6.29
Constitución class	36.88	7.10	170.27	5.36
PBO	46.30	9.10	199.82	5.66
Jayesagara Class	39.80	7.00	329.73	6.69
WPBO	51.50	8.40	838.57	9.13
WPSO	58.90	9.60	1125.89	10.07
WPSO	61.40	9.50	699.73	8.59
Pescalonso class	67.80	11.00	2101.25	12.39
LMSR T-AKR-300	289.99	32.30	61088.74	39.27
AF-58	153.00	22.00	14910.74	24.54
AFS-1	177.00	24.00	18663.00	26.45
T-AKR 287	288.00	32.00	53590.07	37.59
SL-7	288.40	32.00	54475.86	37.80
SS United States	300.00	31.00	46517.56	35.86
STENA HSS 1500	126.60	40.00	19327.86	26.76
Destriero	68.19	13.00	393.68	7.31
LCAC	26.40	14.30	0.00	0.00
SR.N-4 MK2	39.68	23.77	196.84	5.80
HSC INCAT 046	91.30	26.00	5617.00	17.72

Table 5. Ship Type Listings, Correlating Length, Beam, Displacement, and Volumetric Length

Using the displacement of each vessel, I was able to determine a volumetric length by taking the cubed root of the displacement converted to meters. By graphing the values of actual ship length vs. volumetric ship length and finding the equation of the trend line of the data, I was able to come up with an equation solving for ship length based on volumetric length from ship displacement. This graph is shown in Figure 17. The equation we found to relate volumetric length to actual length is displayed in Equation 18.

$$\text{Ship's Actual Length} = 7.7109 \times D^{1/3} - 7.72431 \tag{18}$$

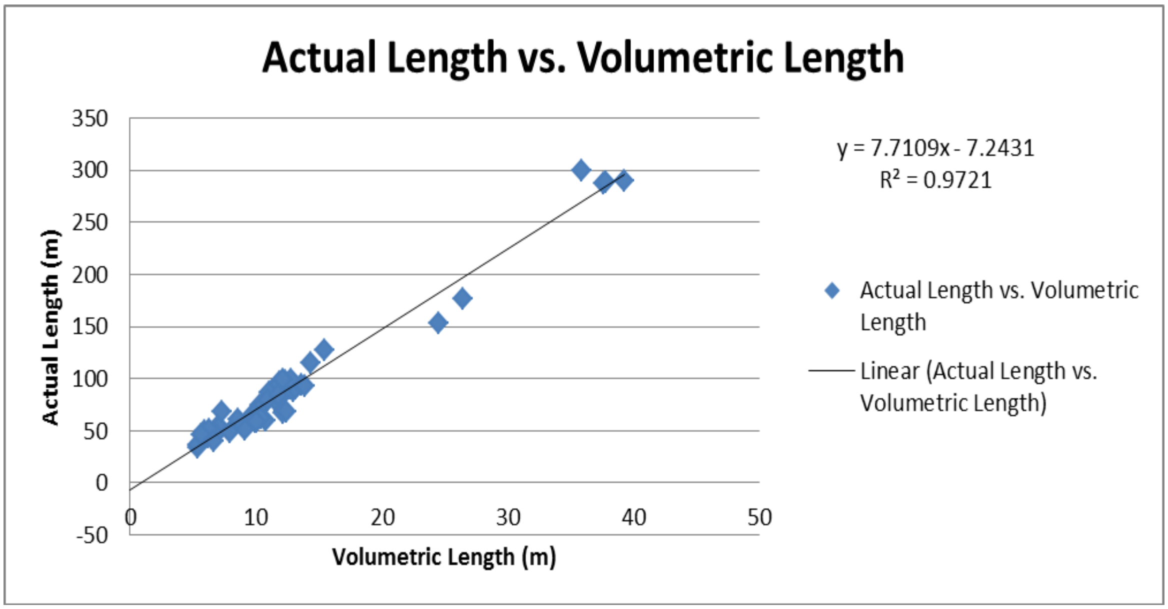

Figure 17. Ship's Actual Length vs. Volumetric Length

Next, I plotted the paired length vs. beam values to find an equation of the data trend to relate the length of the ship to the beam size of the ship. Figure 18 displays this plotted data and trend line below. The formula relating ship length to ship beam length is shown in Equation 19 below.

$$\text{Ship's Beam} = .0975 \times L + 4.1661 \tag{19}$$

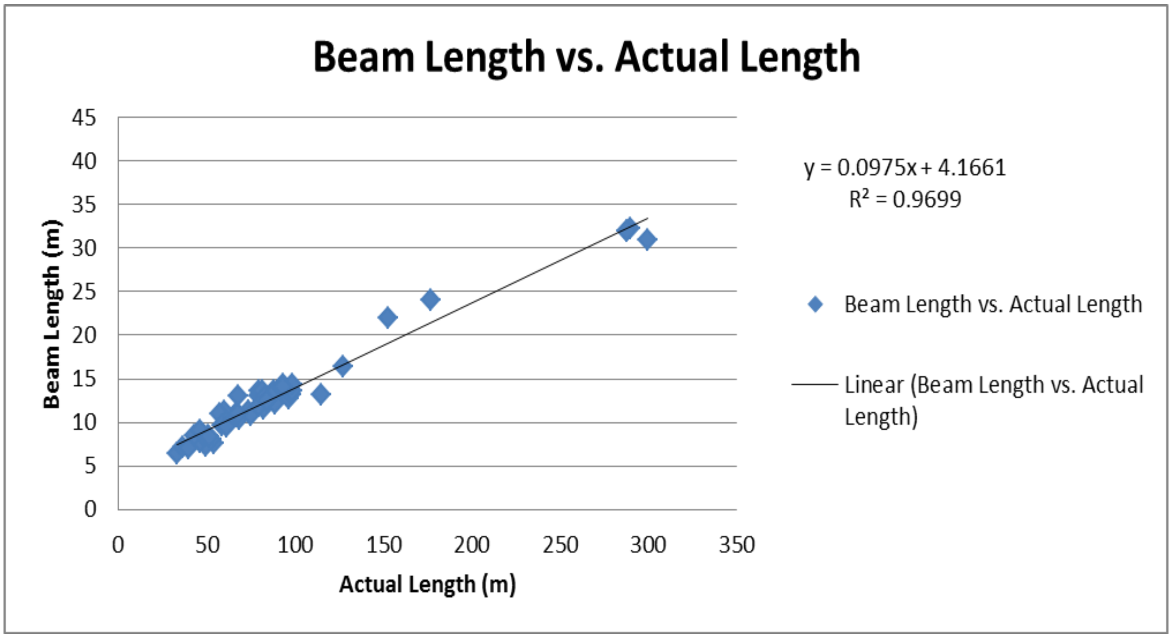

Figure 18. Plotted Actual Ship's Length vs. Beam

Finally, we have concluded that ONR's goal is not attainable, given our assumptions. Now, we will have to utilize this information to determine which one of the assumptions made, most needs to change. The notational calculation above can be repeated for several different ship sizes. The effect of these simple parameters on these highly complex ship systems, conclude that the following suggestions should be implemented in the next simulation to further help achieve the stated goal (McKesson 2006):

- Investigate ways to reduce the Cargo Carriage Multiplier
- Investigate ways to reduce the Weight of Power
- Investigate ways to make substantial improvements in the L/D state of the art
- Investigate ways to make substantial improvements in SFC

D. CONCLUSION

In conclusion, this five-parameter model has provided a tremendous insight into an easy way of accomplishing specific mission requirements. This useful parametric tool also allows a group to access the benefit of an improvement in a design area, so that they can structure a practical and fail-safe research and development investment.

This model, first designed and created by McKesson, allows top-notch ship design assessment to be completed much more rapidly and efficiently. This model can be a very powerful tool in the design of these highly complex systems.

By defining the values that must be attained in order to achieve a given mission capability, the method becomes a powerful tool for assessing the feasibility and benefit of one given design over another. The resultant design framework allows other advances to be built upon it. This example of the five Parameter Method portrayed above is a development and extension of McKesson’s original model.

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V. OPTIMIZATION STUDIES

In this chapter the development of the equations leading to cargo payload will be presented. Cargo load is based on full displacement, speed, propulsive coefficient, specific fuel consumption, range, weight of power, and cargo carriage multiplier.

A. CARGO CARRIAGE LOAD DERIVATION

To begin this chapter we will start off by creating a series of equations to develop an overall encompassing equation for cargo carriage load. In reality, Cargo Carriage Load (CCL) is equal to the full load displacement (D) subtracted by fuel weight (W_f), machinery weight (W_m), and cargo carriage weight (W_{cc}).

$$CCL = D - W_f - W_m - W_{cc} \tag{20}$$

The components of displacement, weight of fuel, weight of machinery, and weight of cargo carriage are all in units of long tons. The formulas for these different components will be broken down into their specific weight formulas.

1. Weight of Fuel derivation

To determine the overall encompassing formula for CCL, we will develop the components and equations that make up fuel weight. The basic equation for weight of fuel is stated in Equation 21.

$$W_f = \frac{SHP \times SFC \times Range_{NM}}{V_K} \tag{21}$$

a. Shaft Horsepower (SHP)

SHP is the overall horsepower of the ship. It is determined from the ratio of effective ship horsepower (EHP) to the overall propulsive coefficient (OPC). Some most common OPC values are depicted in Figure 15. The curve suggests an OPC of 0.60 as a median for propeller ships and fully submerged vehicles.

$$SHP = \frac{EHP}{OPC} \tag{22}$$

EHP is determined from ship resistance and speed. The conversion factor of 33,000 must be used to obtain horsepower from lbs-ft/min.

$$EHP = \text{Resistance} \times \frac{V_{\frac{ft.}{\min.}}}{33000} \tag{23}$$

Ship resistance will be obtained by examining displacement and the lift to drag ratio as shown in Equation 24. The conversion factor of 2,240 must be used to obtain long tons from pounds. Additionally, Equation 25 shows the conversion of velocity in knots, to the needed velocity in ft/min for the EHP equation.

$$\text{Resistance} = \frac{Displacement_{LT}}{(L/D)} \times 2240 \tag{24}$$

$$V_{\frac{ft.}{\min}} = V_K \times 101.269 \tag{25}$$

Equations 26 and 27, and 28 provide the equations for lift to drag ratio, Froude number, and length in meters in which L/D is dependent on. The Froude number is a dimensionless number defined as the ratio of characteristic velocity to the gravitational velocity. It is used to determine the resistance of a partially submerged object moving through water. Equation 29 shows the final outcome of the total resistance equations based on its basic variables for ship speed and displacement.

$$L/D = 5 + (40 \times Fn_{vol}{}^{-3}) \tag{26}$$

$$Fn_{vol} = \frac{V_{m/s}}{\sqrt{9.81 \times L_m}} \tag{27}$$

$$L_m = (D_{LT} \times 35)^{1/3} \times .3048 \tag{28}$$

$$\text{Resistance} = \frac{D \times 2240}{5 + (V_K \times \sqrt{D} \times 2.96564 \times 10^8)} \tag{29}$$

Using the previously stated equations we determine EHP to be equal to the following formula.

$$EHP = \frac{D \times V_K \times 226843}{(5 + (V_K D \times 2.965 \times 10^8))} \tag{30}$$

Therefore, the equation for SHP will be as follows.

$$SHP = \frac{D \times V_K \times 226843}{(5 + (V_K \sqrt{D} \times 2.965 \times 10^8))OPC} \tag{31}$$

b. Specific Fuel Consumption

Another component that must be analyzed and determined for weight of fuel is ship fuel consumption (SFC) which is measured in lbs/hp/hr. Figure 16 shows the SFC reported for a variety of modern turbines in Navy service plotted against their output power.

c. Range and Velocity

The last two components that are needed to determine fuel weight are range (R_{NM}), which is in units of nautical miles and velocity (V_K), which is in units of knots. Usually desired range and velocity are given in the units that are requested of them, so there is no need to provide equations for these two characteristics.

d. Derived Fuel Weight Equation

Implementing the required ship characteristics of SHP, SFC, R_{NM}, V_K, the overall final resulting fuel weight equation simplifies to Equation 32 below.

$$W_f = \frac{D \times 226843 \times SFC \times R_{NM}}{(5 + (V_K \times D \times 2.966 \times 10^8))OPC} \tag{32}$$

2. Weight of Machinery derivation

Weight of Machinery plays a huge factor in the ship's displacement. The equations for machinery weight are as follows. As shown in Equation 33, a ship's machinery weight is equal to the weight of power (W_p) multiplied by SHP, converted to long tons using the conversion factor of 2,240 to convert pounds to LT.

$$W_m = \frac{W_p \times SHP}{2240} \tag{33}$$

Weight of power is assumed for each specific case. In the notational example in the simulations based chapter above, weight of horsepower is assumed to be 10lbs/hp. Implementing the specific equation of SHP as derived in Equation 31, the final equation for machinery weight is fully developed and shown in Equation34.

$$W_m = \frac{D \times V_K \times 226,843 \times W_p}{(5 + (V_K \times \sqrt{D} \times 2.965 \times 10^8))2,240 \times OPC} \tag{34}$$

3. Weight of Cargo Carriage

The basic equation for Cargo Carriage Weight is as follows.

$$W_{cc} = CCL \times CC_{multiplier} \tag{35}$$

However, in order to determine the weight of the cargo carriage we must first consider the weight of the cargo carriage plus the weight of the cargo itself. The cargo carriage multiplier is the number that determines how much extra ship weight must be needed to support each long ton of cargo weight. In the notational example in the simulations based chapter above, the cargo carriage multiplier of 2lbs/lb is used.

Hence, the equation for cargo carriage weight must consider the weight of the cargo load in addition to the cargo carriage.

$$CCL + W_{cc} = CCL + (CCL \times CC_{multipler}) \tag{36}$$

From this equation we can develop a simplified equation for CCL as shown and simplified in Equation 37.

$$CCL = \frac{C\arg oLoad + W_{cc}}{1 + CC_{multiplier}} \tag{37}$$

$$\text{Cargo Load+W}_{\text{cc}} = D - W_f - W_m \tag{38}$$

$$CCL = \frac{D - W_f - W_m}{1 + CCM} \tag{39}$$

4. Putting it All Together

Using the equations derived above, we can now determine a thorough equation for the specific cargo carriage load. Implementing the equations specified above for, weight of fuel, weight of machinery, and weight of cargo carriage, we get a final simplified equation for cargo carriage load.

$$CCL = \frac{D - \left(\frac{D \times 226843 \times SFC \times R_{NM}}{(5 + (V_K \times \sqrt{D} \times 2.9056 \times 10^8))OPC}\right) - \left(\frac{W_p \times D \times V_K \times 226843}{(5 + (V_K \times \sqrt{D} \times 2.9056 \times 10^8))2240 \times OPC}\right)}{1 + CCM} \quad (40)$$

5. In Summary

In summary, the equations determined above represent the derivation of finding Cargo Carriage Load (CCL). The simplified, non-iterative basic equations are as follows.

$$CCL = \frac{C\arg oLoad + W_{cc}}{1 + CC_{multiplier}}$$

$$\text{Cargo Load} + W_{cc} = D - W_f - W_m$$

$$W_f = \frac{D \times 226843 \times SFC \times R_{NM}}{(5 + (V_K \times \sqrt{D} \times 2.966 \times 10^8))OPC}$$

$$W_m = \frac{D \times V_K \times 226{,}843 \times W_p}{(5 + (V_K \times D \times 2.965 \times 10^8))2{,}240 \times OPC}$$

Substituting the following equations for Cargo Load+W_{cc} produces Equation 40 for overall cargo carriage load which is repeated below.

$$CCL = \frac{D - \left(\frac{D \times 226843 \times SFC \times R_{NM}}{(5 + (V_K \times \sqrt{D} \times 2.9056 \times 10^8))OPC}\right) - \left(\frac{W_p \times D \times V_K \times 226843}{(5 + (V_K \times \sqrt{D} \times 2.9056 \times 10^8))2240 \times OPC}\right)}{1 + CCM}$$

B. LENGTH & BEAM DERIVATION

From knowing a certain ship's displacement, one can now determine a likely approximate ship length and beam size based on the ship data graphed above in Figure 17 and 18 and their respective trend line functions displayed in Equations 18 & 19. These two equations, repeated below, portray the typical trend line function based on typical ship length and beam sizes of over fifty ship sizes and displacements. From the plotted data of actual length vs. volumetric length, the following equations portray the outcome from the trend line function. In these cases L_A and L_V stand for actual and volumetric length respectively.

$$L_A = (7.7109 \times L_v)\text{-}7.2431 \tag{18}$$

L_V is determined from volume which is determined from displacement in long tons.

$$L_V = (D \times 35)^{1/3} \times .3048$$

Combining and simplifying the two above equations result in Equation 41, as follows.

$$L_A = 7.68793 \times D^{1/3} - 7.2431 \tag{41}$$

From using the ship characteristic sizes and plotting a graph of beam vs. actual length the trend line function displays a relationship for beam length as shown in Equation 19 which is repeated below.

$$B = (0.0975 \times \mathrm{L}_A) + 4.1661 \tag{19}$$

Incorporating the formulas for actual and volumetric length into the trend line beam function, a final equation for beam length is displayed in Equation 42 below.

$$B = .749573 \times D^{1/3} + 3.45999 \tag{42}$$

VI. RESULTS AND CONCLUSIONS

Typical results based on the mathematical models developed above are presented below. In order to present and discuss the results, we have to introduce a few variables. These variables are presented in Table 6.

Variable	Expanded Name	Description
Risk Size	N/A	Area of risk disk
ECargo##	Estimated Cargo for a specific outcome	The amount of expected delivered cargo when considering risk of a specific outcome. Ex: ECargo32=Estimated Cargo delivered for a 3 ship case, where only two ships survive.
ETCargo	Estimated Total Cargo	The total amount of expected delivered cargo, when analyzing risk, for all of the possible outcomes that can occur in one simulation of a specific number of ships
pRatio	Raw Cargo/D	Raw Cargo (cargo without risk consideration) divided by individual ship displacement. LT_{Cargo} per $LT_{Displacement}$
*look at MATLAB code for clearer understanding and demonstration of a three ship simulation		

Table 6. Table of Variables

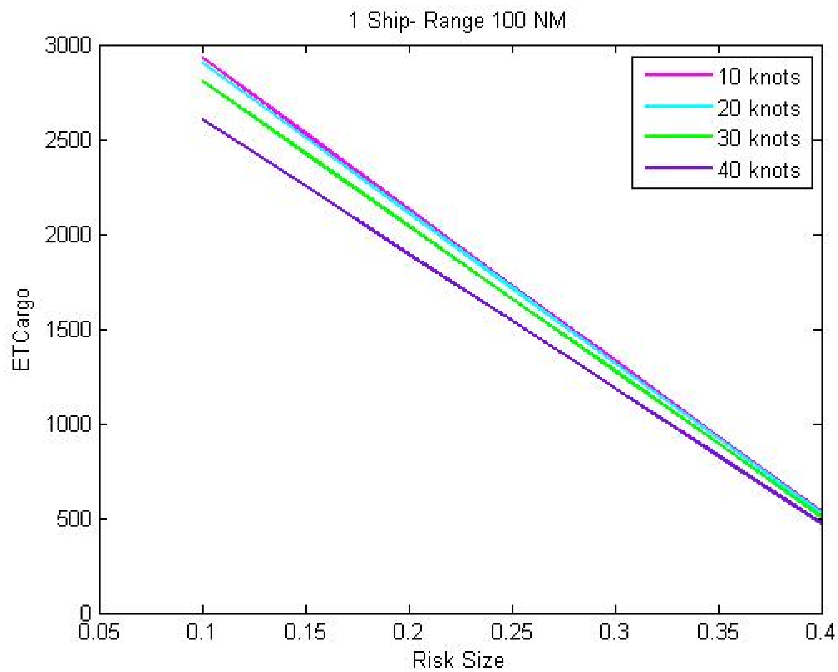

Figure 19. ETCargo vs. Risk Size, Single Ship, Range of 100NM, Varying Speed

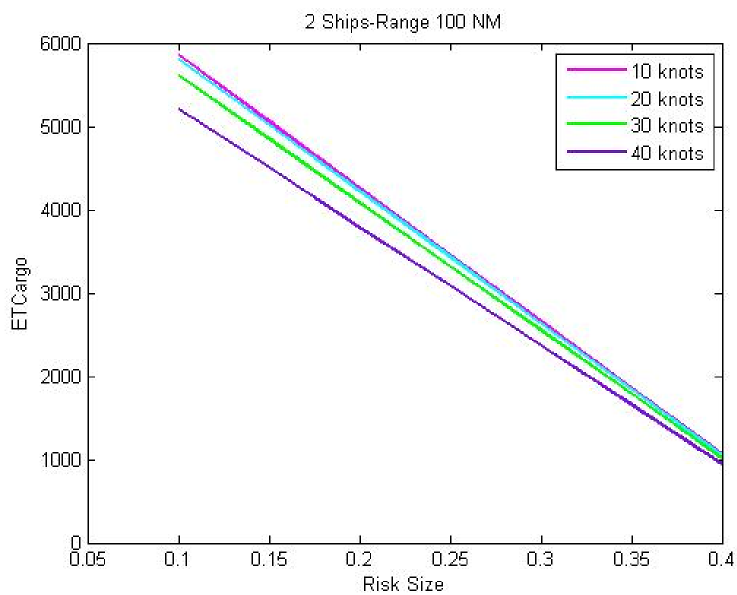

Figure 20. ETCargo vs. Risk Size, Two Ships, Range of 100NM, Varying Speed

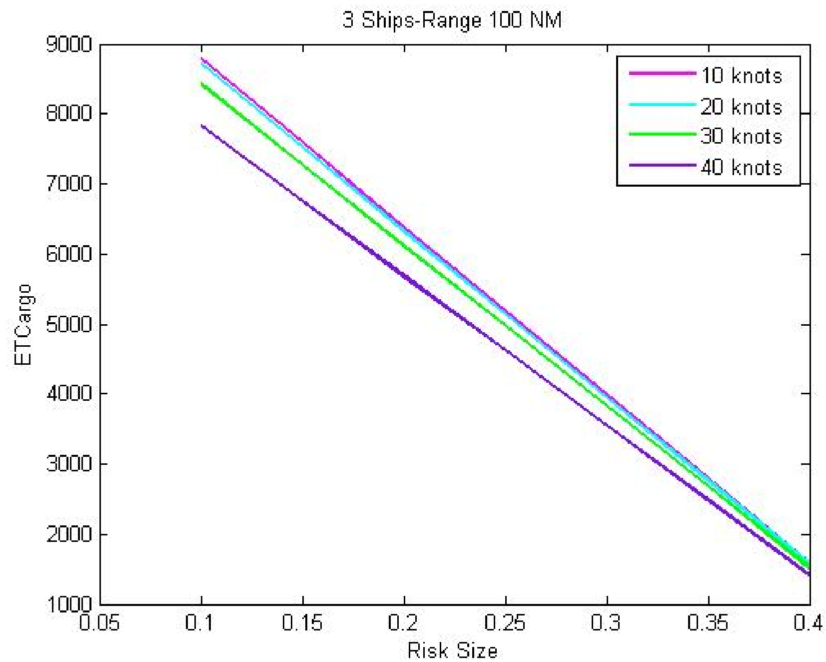

Figure 21. ETCargo vs. Risk Size, Three Ships, Range of 100NM, Varying Speed

Figures 19 through 21 demonstrate the trends occurring between ETCargo and risk size, as range remains constant at 100NM and speed varies from 10 to 40 knots. As mentioned above in Table 6, ETCargo is the total amount of expected delivered cargo, when analyzing risk, for all of the possible outcomes that can occur in one simulation of a specific number of ships. As predicted, the expected payload decreases for increasing risk. It can be seen that the payload, for a given risk, is decreasing for increasing speeds. This is due to the fact that increasing speeds result in additional fuel demands, leaving less weight available for cargo. It should be emphasized, however, that this is true for a single run-through of increasing risk area and does not take into consideration the fact that a vessel with a higher speed will be able to complete multiple trips in a given operational window.

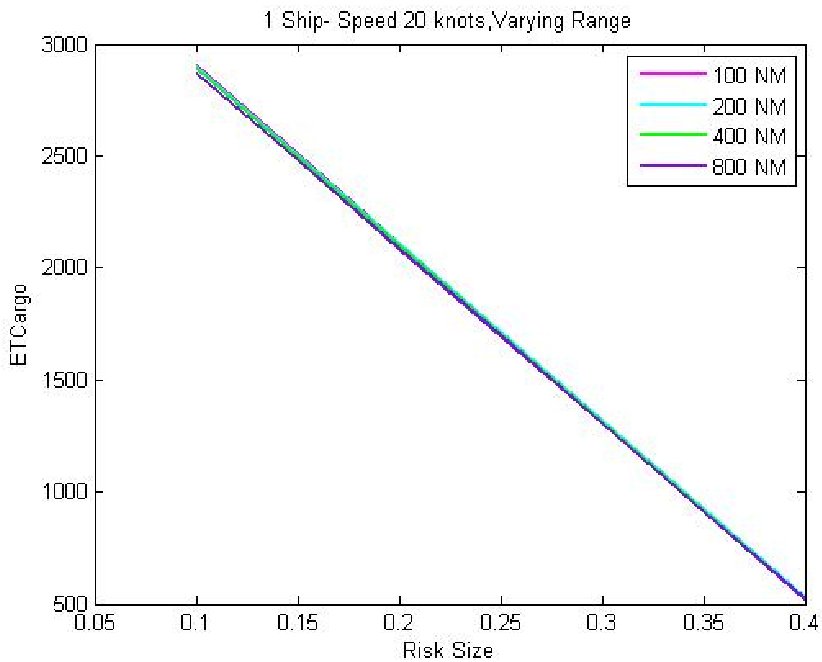

Figure 22. ETCargo vs. Risk Size, Single Ship, Speed of 20 knots, Varying Range

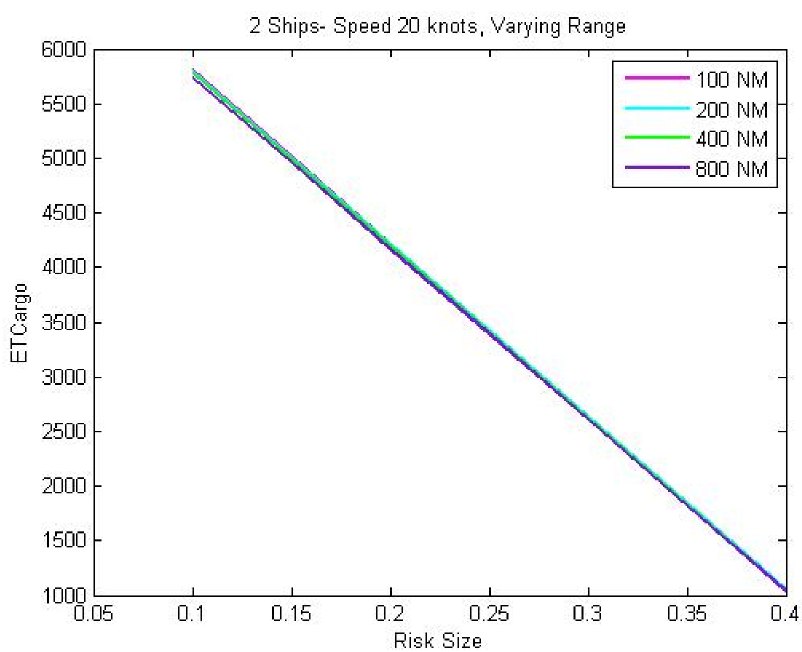

Figure 23. ETCargo vs. Risk Size, Two Ships, Speed of 20 knots, Varying Range

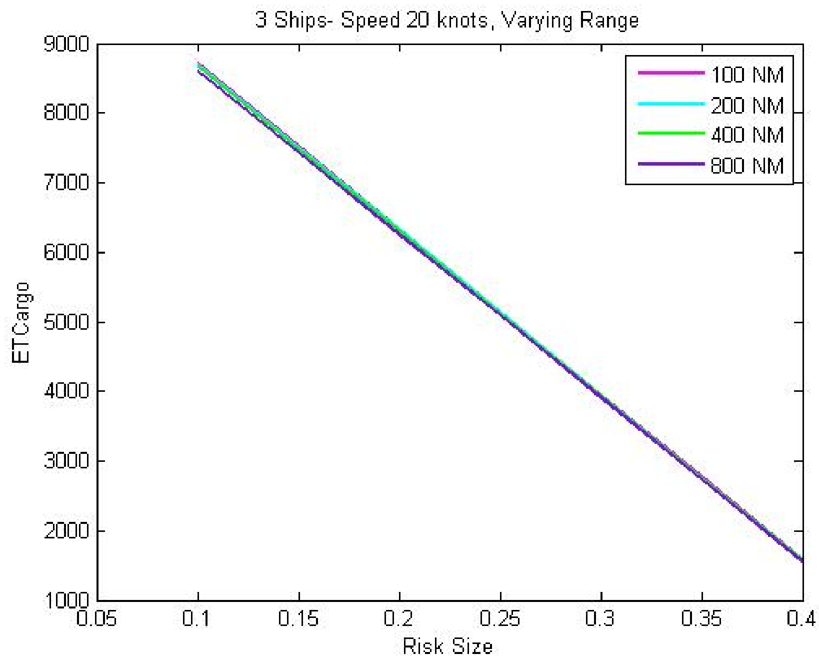

Figure 24. ETCargo vs. Risk Size, Three ships, Speed of 20knots, Varying Range

Figures 22 through 24 demonstrate the trends occurring between ETCargo and Risk Size, as speed remains constant at 20knots and range varies from 100 to 800NM. Similar to the previous set of graphs, the expected value of the payload is decreasing for an increasing risk area. The dependency on range is, however, less pronounced than speed. This is due to the single run-through of the results and does not take into consideration that an increased range might result in multiple run-throughs as the need for refueling is decreased.

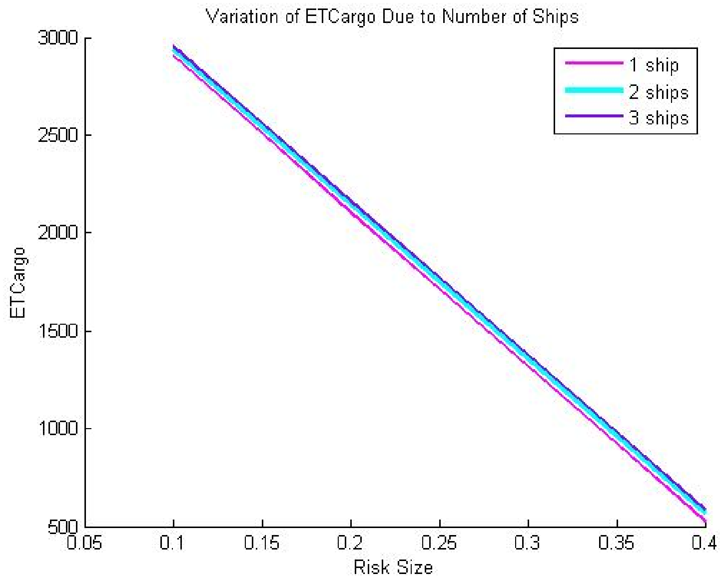

Figure 25. ETCargo vs. Risk Size, Varying Ship Quantities

Figure 25 portrays the outcomes of ETCargo with respect to risk size as additional number of ships travel through the area. It can be concluded from Figure 25 that it is slightly more beneficial to have a larger number of ships. As indicated from the above figure, as the number of ships increase, the amount of cargo delivered increases as well. It should be mentioned that for this test, displacement was held constant. The different runs of the one, two, and three ship cases had displacements of 12,000, 6,000, 4,000 LTs respectively, so that the total displacement of each scenario was 12,000LT.

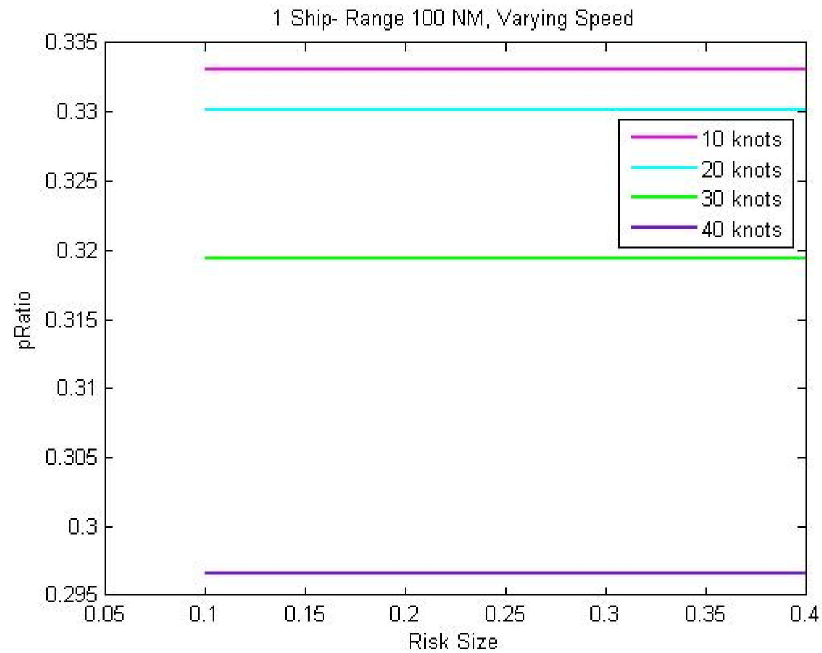

Figure 26. pRatio vs. Risk Size, Single Ship, Range of 100 NM, Varying Speed

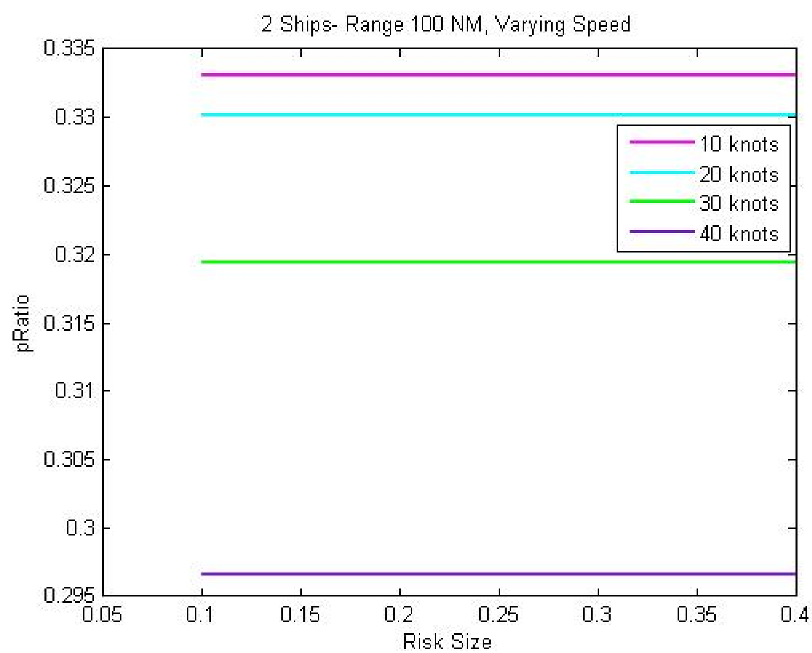

Figure 27. pRatio vs. Risk Size, Two Ships, Range of 100 NM, Varying Speed

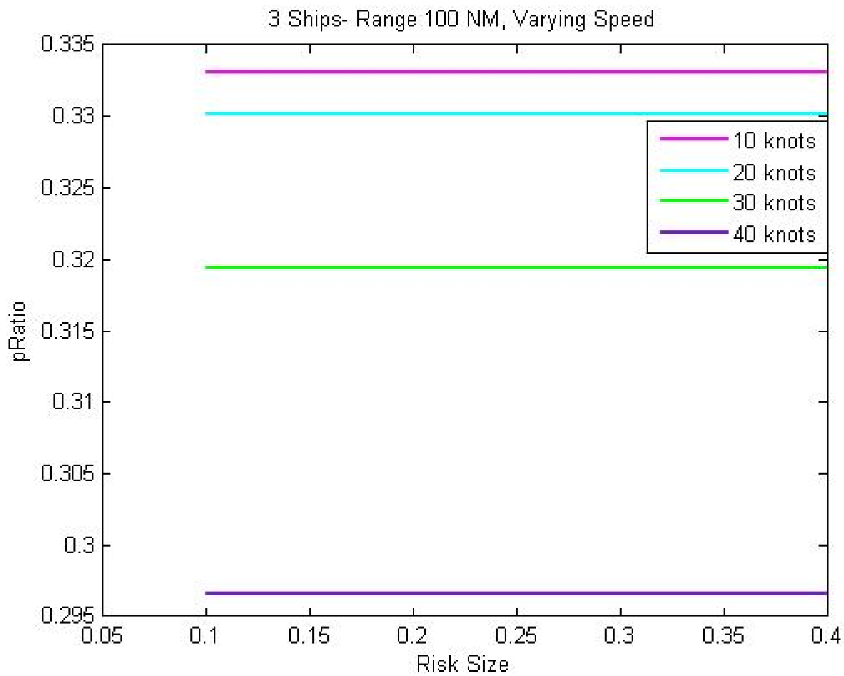

Figure 28. pRatio vs. Risk Size, Three Ships, Range of 100 NM, Varying Speed

Figures 26 through 28 demonstrate the trends occurring between pRatio and risk size, as range remains constant at 100NM and speed varies from 10 to 40 knots. As stated above in Table 6, pRatio is the ratio of raw cargo, the maximum cargo able to be delivered with no risk considerations, divided by individual ship displacement. In these cases, pRatio remains constant as risk size increases, since raw cargo is not dependent on risk size. We notice that for the slower speeds, the ship is able to carry more cargo per ton of displacement. But again, it should be emphasized that this is true for a single run-through a risk area and does not take into consideration the fact that a vessel with a higher speed will be able to complete multiple trips in a given operational window.

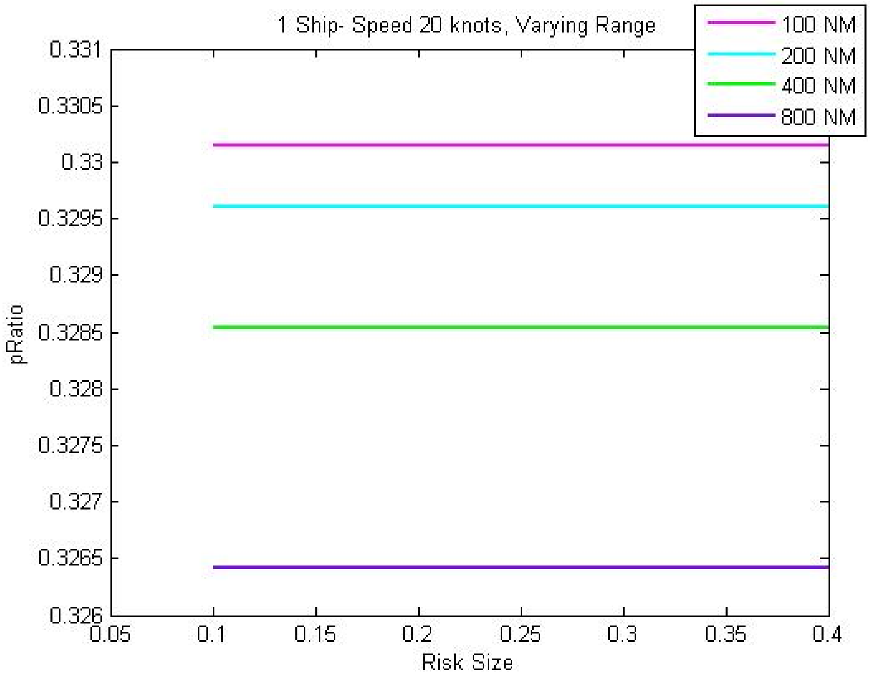

Figure 29. pRatio vs. Risk Size, Single Ship, Speed at 20 knots, Varying Range

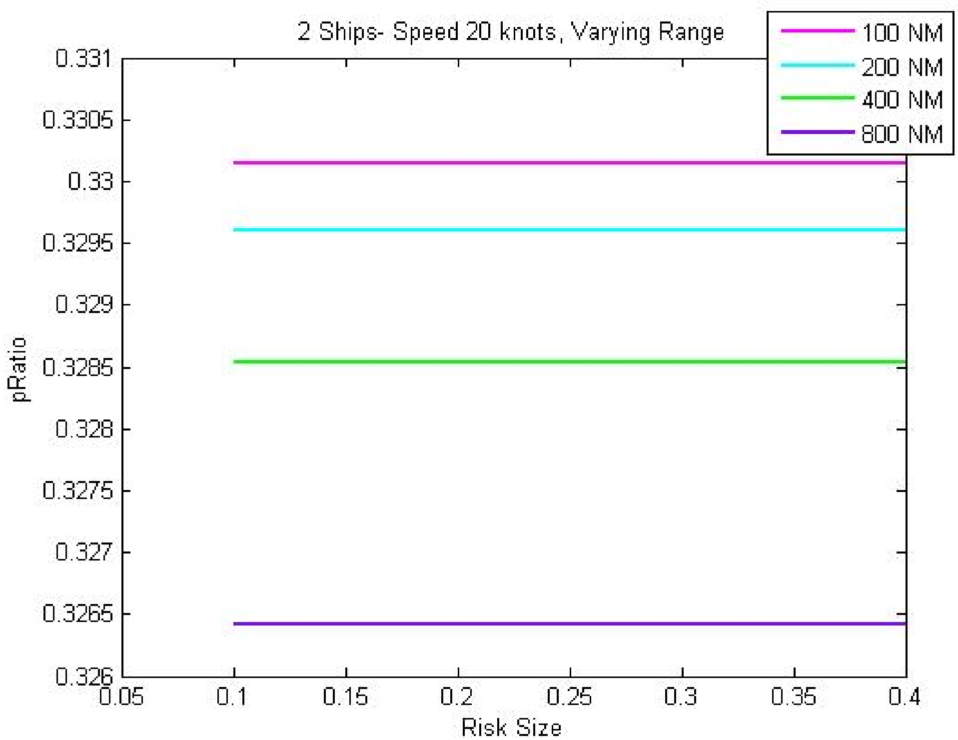

Figure 30. pRatio vs. Risk Size, Two Ships, Speed of 20 knots, Varying Range

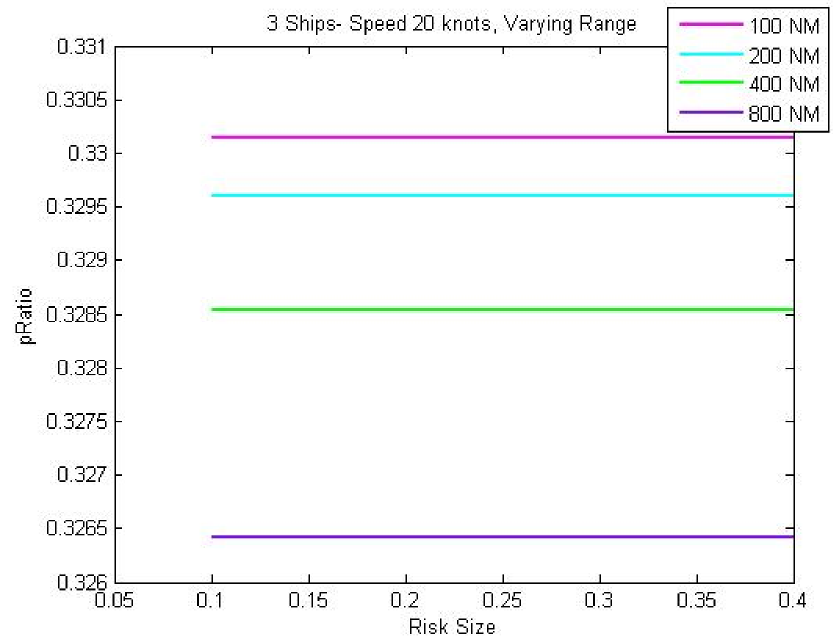

Figure 31. pRatio vs. Risk Size, Three Ships, Speed at 20 knots, Varying Range

Figures 29 through 31 demonstrate the trends occurring between pRatio and risk size, as speed remains constant at 20 knots and range varies from 100 to 800NM. In these cases, again pRatio remains constant as risk size increases, since raw cargo is not dependent on risk size. We notice from these figures that for shorter ranges the cargo ships are able to successfully deliver more payload than when traveling longer distances. This is due to the fact that there is more room for cargo space, rather than fuel space. However, the positive effects of shorter range would be diminished if a multiple run through case was conducted. The increased range in a multiple run through case would account for the ship being able to make more trips with its need for refueling decreasing and would allow more cargo per ton to be delivered.

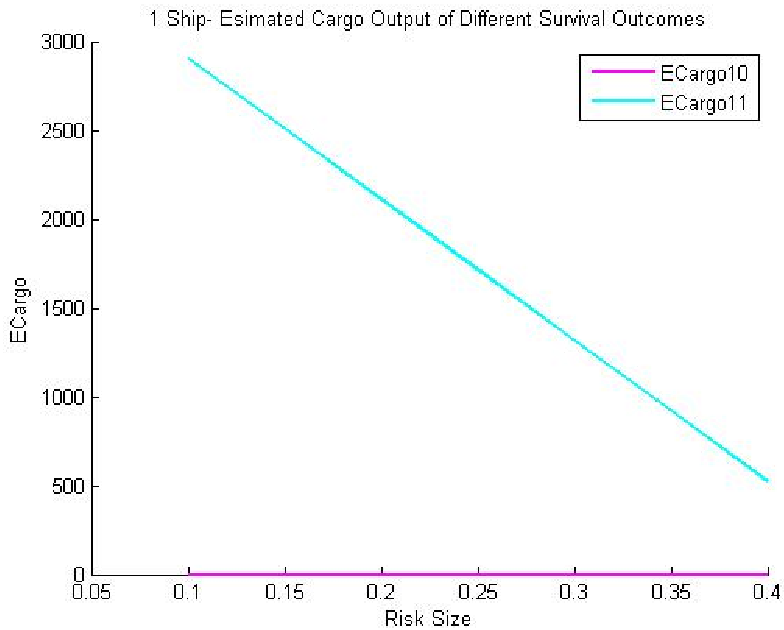

Figure 32. ECargo vs. Risk Size, Single Ship

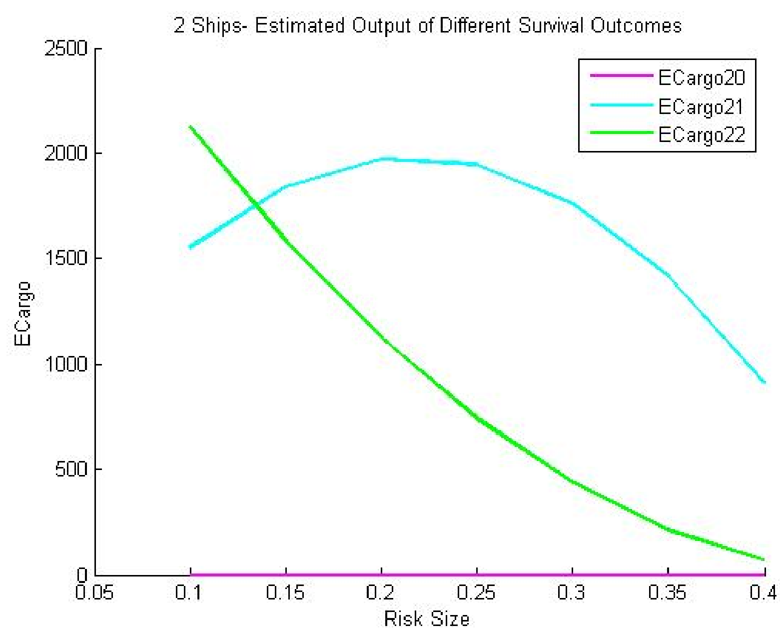

Figure 33. ECargo vs. Risk Size, Two Ships

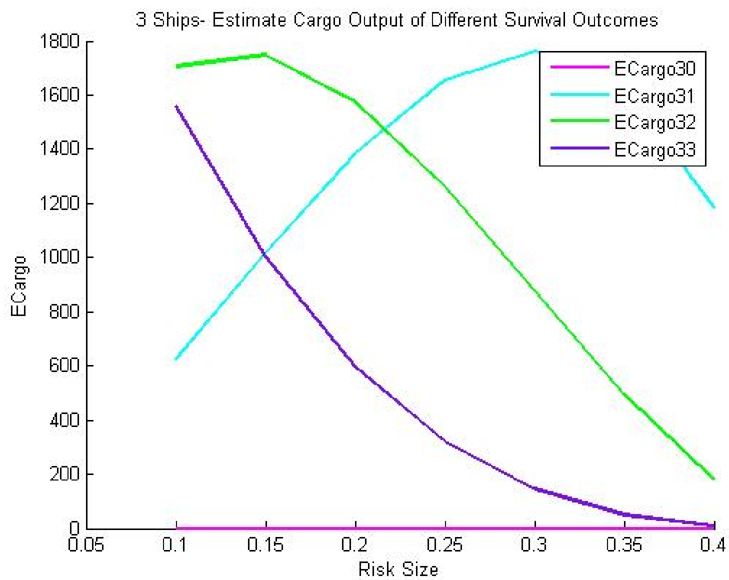

Figure 34. ECargo vs. Risk Size, Three Ships

Figures 32 through 34 demonstrate the trends occurring between ECargo and risk size for each different survival outcome. As stated in Table 6, ECargo is the amount of expected delivered cargo when considering risk of a specific outcome. For instance, ECargo32, as shown in the above Figure 39, stands for the expected cargo of a three ship case, where only two ships survive. The same goes for ECargo33. ECargo33 is the expected cargo of a three ship case with all three ships surviving. These three graphs above show the expected value of the delivered payload for each ship case depending on different survivability outcomes. It can be seen that the relationship is not always monotonic. The final expected value of the delivered payload will be the aggregate of the individual outcomes shown in the figure.

In conclusion, we have achieved our goal to create an analytic model for payload delivery rates through an area of risk. The model is based on data from existing ships and is flexible enough so that it can be easily modified when new ship data or types are introduced. The risk is modeled through analytically derived survivability formulas. This model is also flexible enough so that it can be modified to account for different types of risk.

As presented in the results of tests and simulations completed, the model can offer insight on many design decisions during the early stages of a design and can assess the suitability or benefit of a given design over another in an operational scenario.

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VII. RECOMMENDATIONS

There have been several recommendation ideas that this current research has inspired for future study. The current model assumes that each ship passes through an area of risk only once. If the model is suitably modified to allow for multiple pass-throughs, then the model can better show the effects of speed and range.

The same is true for information gathering. The current model assumes that there is no information exchange between the various ships, which allows the probabilities of hits to be treated as statistically independent events. If we allow some amount of information exchange, then we can model better the effects of different ship routes of travel through an area of risk. This may have an impact on tactics, or formation and swarm control in the case of unmanned systems.

Additionally, we can also modify the risk area to allow for a probability of actuation. The current model assumes a certain hit and kill for the ship as it enters the risk disk. If we allow for a probability of actuation or a probability of kill we can better model the effects of certain threats or the effects of larger ship sizes. Finally, if we allow for a binary variable to model the probability of survival of the risk disk following a hit, we can then better distinguish between different risk types such as permanent and disposable units.

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APPENDIX: MATLAB CODE FOR THREE SHIP CASE

```
clc

%D   = input ('Displacement (LT) = ');
%Vk  = input ('Speed (knots) = ');
%OPC = input ('Propulsive Coefficient = ');
%SFC = input ('Specific Fuel Consumption (lbs/hp/hr) = ');
%R   = input ('Range (NM) = ');
%Wt  = input ('Unit Power Weight (lbs/hp) =');
%CCM = input ('Cargo Carriage Multiplier (lbs/lbs) =');

D1=12000;
Vk=20;
%Vk=linspace(10,40,7);
OPC=0.6;
SFC=0.4;
R=100;
%R=linspace(100,1000,7);
Wp=10;
CCM=2;

% 3 Ships
for i=1:7
D3=D1
Vol = D3*35;
VLength = (Vol)^(1/3)*0.3048;
V= 0.514444*Vk;
V1= V*60/0.3048;
VFn = V/(9.81*VLength)^(1/2);
LDratio = 5 + 40*VFn^(-3);
Res = (D3/LDratio)*2240;
EHP = (Res * V1)/33000;
SHP = EHP/OPC;
WF = SHP*SFC*R/Vk;
WF3=WF/2240;
Cargo3 = (D3-WF3-(Wp*SHP/2240))/(1+CCM);
Length = 7.7109*VLength - 7.72431;
Beam = 0.0975*Length + 4.1661;
Width = 1000*.3048;
R1=linspace(100,400,7);
Risk(i) = R1(i)*.3048;
r(i) = Risk(i)/Width;
b = Beam/Width;
PS0(i) = (b+2*r(i))^3;
ECargo30(i)=Cargo3*PS0(i);
PS1(i) = [(1-b-2*r(i))*(b+2*r(i))^2]*3
ECargo31(i)=Cargo3*PS1(i)
PS2(i) = [((1-b-2*r(i))^2)*(b+2*r(i))]*3
ECargo32(i)=Cargo3*PS2(i)
PS3(i) = (1-b-2*r(i))^3
ECargo33(i)=Cargo3*PS3(i)
```

```
x(i)=PS0(i)+PS1(i)+PS2(i)+PS3(i)

ETCargo(i)=ECargo30(i)*0+ECargo31(i)*1+ECargo32(i)*2+ECargo33(i)*3
%Estimated Total Cargo
pRatio(i)=Cargo3/D3                                %Raw cargo per LT
cRatio(i)=ETCargo(i)/(3*Cargo3)                   %Estimated predicted
cargo per raw cargo
end
```

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